FINAL REPORT

NUCLEAR REACTIONS IN GaAs AND SI
AND
THEIR ROLE IN THE SINGLE EVENT
UPSET PROBLEM

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1. ACCOMPLISHMENTS

CHARGE COLLECTION MEASUREMENTS

Experiments were carried out to measure charge collection resulting from exposure of Rockwell Fat-FET test structures to alphas, heavy ions and protons. The alpha and heavy ion data were used to determine the dimensions of the sensitive volume following techniques outlined in Appendix A.

Charge collection measurements in Si PIN photodiodes were carried out. This represents the first test of the ability of the CUPID codes to handle partially depleted n-p junctions. Measurements were made with two devices. The UV-100 PIN photodiode from EG+G had a sensitive volume which was only partially depleted even at high voltages, the YAG 444 is fully depleted over its thickness (400 um) when fully biased but the depletion width is substantially reduced for low biases. *Gallium Arsenide , Silicon . (Proton)*

MODELING CHARGE COLLECTION

The CUPID codes were modified to include circuits implemented in GaAs. This required significant changes to the nuclear reaction codes and the transport portions of the codes. In order to test the new revision of the codes, we carried out the experimental charge collection

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measurements described in the previous section. The lateral dimensions of the sensitive volume were taken to be the lateral dimensions of the junction as seen under a microscope. The thickness of the sensitive volume was estimated from the energy deposition spectra obtained with Americium-241 of the type shown in Fig. 2a and 2b of Appendix A.

COMPARISON OF HEAVY ION AND PROTON DATA

If our models of SEU phenomena are correct, one ought to be able to use the heavy-ion data from accelerator runs to predict the SEU data from proton-induced nuclear reactions. Successful predictions would confirm the basic model, the values used for the critical charge, and the dimensions used for the sensitive volume. Appendices B and C describe two attempts in this direction which show considerable success. Future efforts will be aimed at using proton data to predict the heavy-ion response because proton irradiations are cheaper and easier to carry out.

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2. PUBLICATIONS, THESIS AND PAPER PRESENTED

A. The following papers based on work carried out under this contract were published.

1) "Methods for Calculating SEU Rates for Bipolar and NMOS Circuits",P.J. McNulty, W.G. Abdel-Kader, and J.M. Bisgrove IEEE Trans. Nucl. Sci. NS-32, 4180-4184 (1985). (See Appendix B)

2) "Comparison of Soft Errors Induced by Heavy Ions and Protons", P.J. McNulty, J.M. Bisgrove, J.E. Lynch, W.G.Abdel-Kader, and W.A. Kolasinski IEEE Trans. Nucl. Sci. NS-33 1571-1576 (1986). (See Appendix C).

B. The following papers based on work carried out in part under this contract was submitted for presentation at the GaAs IC Symposium.

1) "Charge Collection in Partially Depleted GaAs Test Structures Induced by Alphas, Heavy Ions and Protons. Shadia El-Teleaty, P.J. McNulty and W.G.Abdel-Kader.

C. The following tutorial was prepared for presentation at the annual Single Event Upset Phenomena Workshop under this contract.

1) "FUNDAMENTALS of SINGLE EVENT PHENOMENA" by P.J. McNulty.

D. The following theses supported in part by this contract were submitted.

1) "Soft Errors Induced by Energetic Protons in VLSI dRAMs" Submitted by Jeff Bisgrove for MS degree 1985.

2) "Charge Collection Within Well Defined Microstructures Induced by the Nuclear Reactions of High Energy Protons" Submitted by Shadia El-Teleaty for the Ph.D. degree in 1987.

APPENDIX A

CHARGE COLLECTION IN PARTIALLY DEPLETED
GaAs TEST STRUCTURES*

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ABSTRACT

Charge collection in Rockwell Fat FET GaAs test structures for events induced by alphas, heavy ions and proton-induced nuclear reactions were measured for variety of bias values and two doping levels. Analysis of heavy ion data provided the shape and dimensions of the sensitive volume. Comparison of proton data and simulations using CUPID codes, assuming this sensitive volume, yield agreement.

INTRODUCTION

The mechanism by which single-event upset (SEU) events are initiated in Si and GaAs circuits is the collection of more than a critical charge at a sensitive structure within some time interval. This time is determined by the circuits of which the structure is a part. Circuits can be hardened against SEUs by increasing the critical charge, altering the time constants of the circuit, or introducing fault-tolerant algorithms into the system architecture. However, the application of any of these fixes with a minimum of performance tradeoff requires precise knowledge of the SEU rates to be expected before and after the fix. This, in turn, requires a quantitive understanding of the charge collection at the SEU-sensitive junctions of the circuits.

The CUPID (Clarkson University Proton Interactions in Devices) codes have been shown to accurately predict the charge generation in fully depleted Si surface-barrier detectors over a wide range of incident proton energies where the thickness of the detectors was varied from 2.5 to 97 μm (1-3). However, the codes have never been proven to work for GaAs devices nor have they been tested against measurements with partially depleted structures in either GaAs or silicon. The codes have been shown to be useful in predicting proton-induced SEUs from first principles for devices for which sufficient process information was known and from heavy-ion data for a variety of other Si device types. Some of these devices included SEU-sensitive structures which were partially depleted. This paper presents the first published results from a comparison of CUPID calculations with charge-collection (CC) measurements in GaAs structures.

The objective of this study was to derive a simple procedure for calculating the charge collection in partially depleted detectors exposed to energetic protons using the GaAs version of the CUPID codes (4). The first approach tried was to test the first-order approach used in all SEU algorithms for calculating rates in space(5-7), i.e. represent the sensitive junction by an equivalent sensitive volume. The lateral dimensions of the sensitive volume are those of the junction while the thickness is chosen to be such that the charge generated within the equivalent sensitive volume in the simulation calculations equals the the charge

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that would have been collected at the real junction (8,9).

We will show comparisons between measurements and simulation calculation for GaAs test structures, the fatFET structures on Rockwell's GaAs memories. The comparison is done for different energies, biases, and doping profiles.

EXPERIMENTAL PROCEDURE

The experimental set up of these measurements is shown in Fig. 1. All the proton exposures were done at Harvard University's Cyclotron using 25 to 158 MeV protons. The heavy-ion exposures were done at University of Pittsburgh. The GaAs FatFET test structures are tested for two different types (N^- and $N^- + N^+$). The difference between the recent and the previous study (3) is that the devices in that case were fully depleted Si devices and the only contribution to the CC was the drift component. In this study, the devices are partially depleted and there are two extra components contributing: the field assisted drift (funneling) and diffusion. Also, the test structures are made from GaAs not silicon.

GaAs Test Structure:

The gates of the Rockwell (1K RAM) GaAs MESFET test structures were negatively biased with the source and drain grounded. Test structures were available with light (N^-) and heavy (N^+) doping under the gate electrode. The effective thickness of the sensitive volume was quite sensitive to the bias when the lighter doping is used.

To use the CUPID codes to predict the CC in partially depleted devices, we estimate the thickness of the sensitive volume from exposure to Am^{241} alphas. Figures 2a and 2b show examples of the CC spectra for GaAs test structures. The position of the peak is used to determine the effective thickness of the sensitive volume and the high energy tail is used to estimate the dimensions of the small enhanced-collection regions (10) at the edges of the 145 μm x 350 μm structure.

RESULTS

Comparisons between the simulation calculations and the experimental data are done for the two test structures. Figures 3 through 5 show the comparison of $N^- + N^+$ for energies 25 to 158 MeV protons. Also, similar comparison is shown in Fig. 6 and Fig. 7 for N^-. The agreement is good for the high energies. The GaAs version of the CUPID codes contains a programming error in which the code generates the wrong number of events emerging from the reactions at low incident energies (less than 70 MeV). For this reason, the comparisons below 70 MeV are done by normalizing the model calculations to the total number of events to be expected in the SV plus surround, and the known total cross-section. The comparison is quite good.

An interesting feature of the comparisons is that the model predicts that the pulse-height spectra falls sharply as the proton energy is decreased while the experimental spectra shows small by decreasees in the slope as the incident energy decreases.

Figures 8 and 9 plots the charge collected at the junction versus the incident particle's LET showing a near linear relationship when the bias are zero and -1.2 volts respectively. A linear relationship is a necessary assumption for models which increase the thickness of the SV to account for the charge collection by funneling and diffusion. The assumption appears to be reasonable for GaAs over the range of LET values corresponding to the abundant cosmic-rays. In the final manuscript, more proton exposures and their comparison with the CUPID code will be presented.

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CONCLUSION

In conclusion, the CUPID codes combined with simple assumptions regarding funneling and diffusion appear to be quite accurate in simulating the charge collection of GaAs test structure for high proton energies. More work is needed for low proton energies but the assumption of little or no change from higher energies appears to be reasonable. The model predicts a dramatic decrease in the pulse-height spectra for low proton energies which is not observed experimentally. The simple assumptions regarding funneling and diffusion contributions to the collected charge that were used here appear to give reliable results. Until now, we had tested this method by using three different devices, one of them in this manuscript and the rest in ref. (8,9). It seems that the devices which are tested have a simple structure. For complicated structures (i.e. CMOS) more work needs to be done to confirm that the method can be used with the CUPID codes to predict the CC in all the test structures (Si or GaAs).

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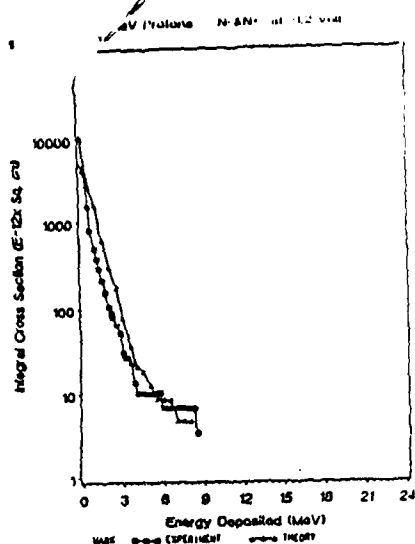
Fig. 1

Fig. 2a

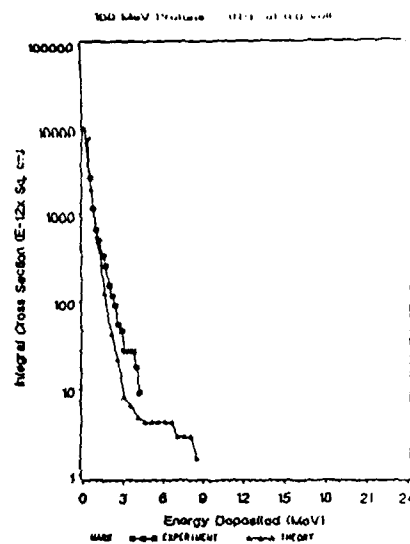Fig. 2b

Fig. 3a

Fig. 3b

Fig. 4a

Fig.4b

Fig. 5a

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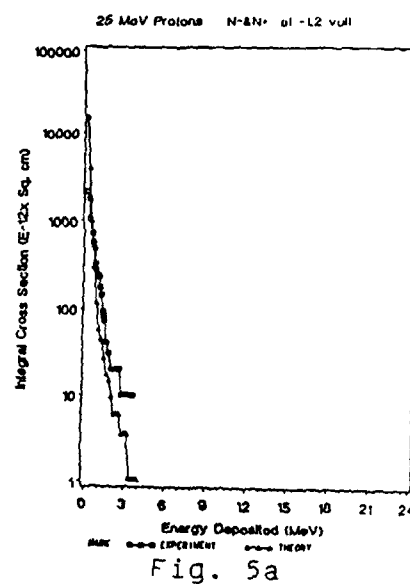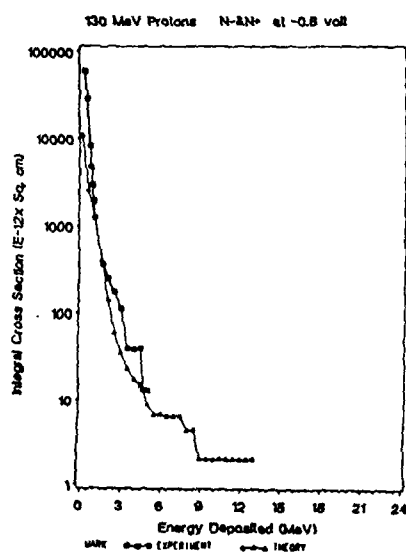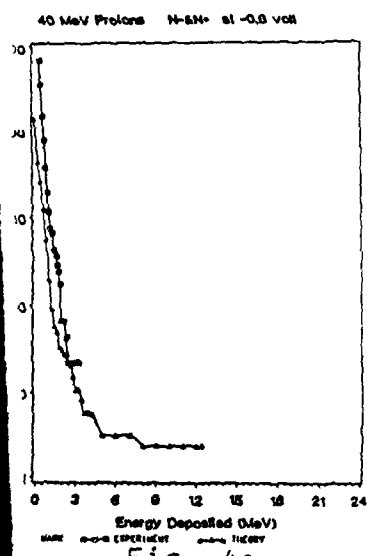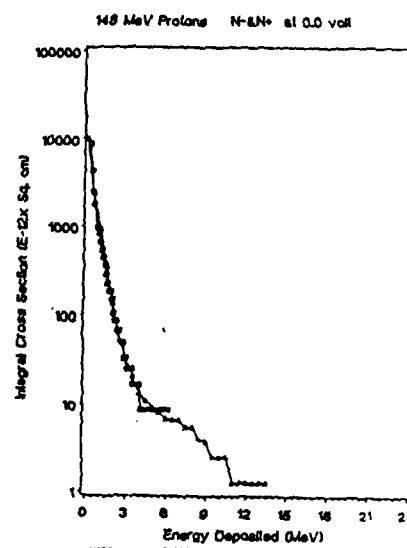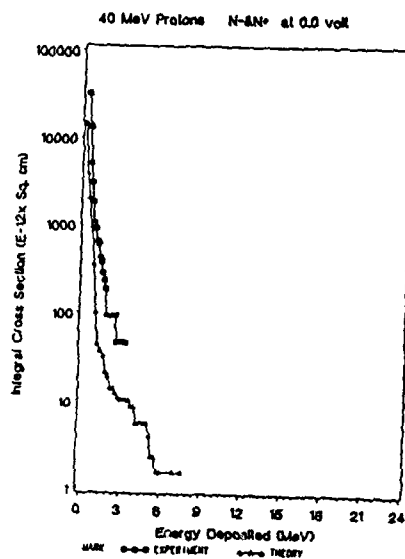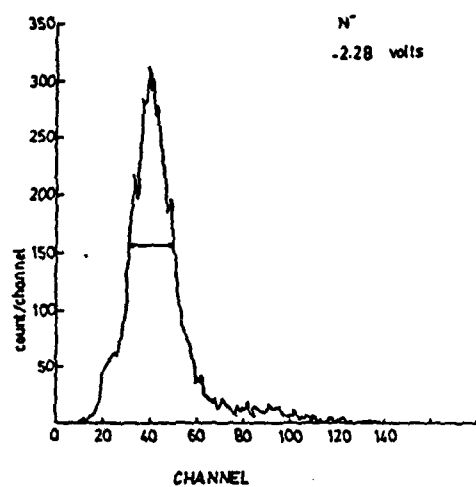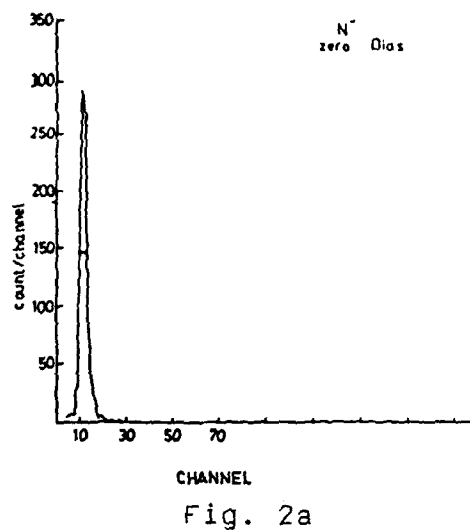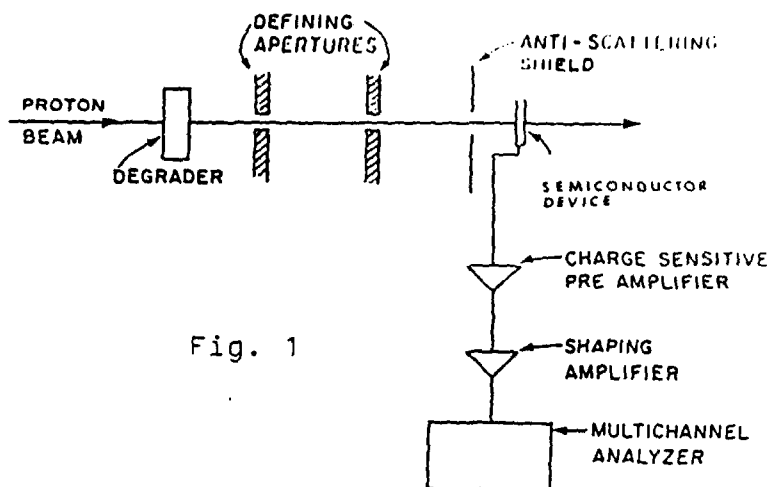
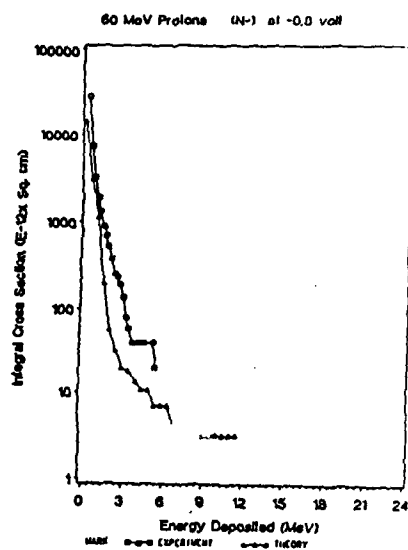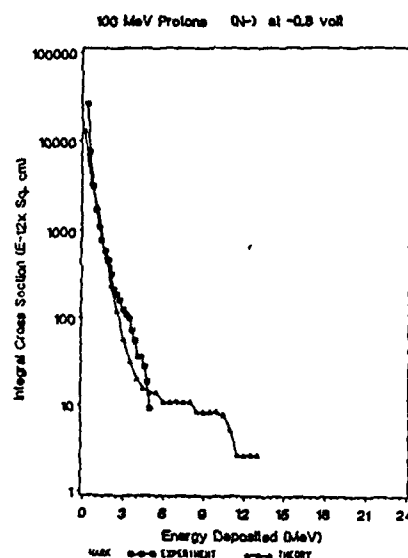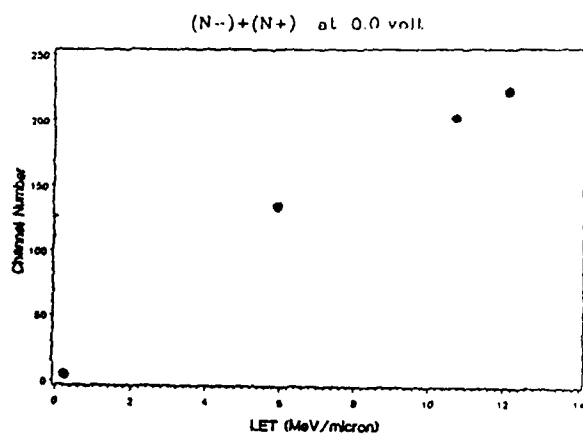Fig. 5b

Fig. 6a

Fig. 6b
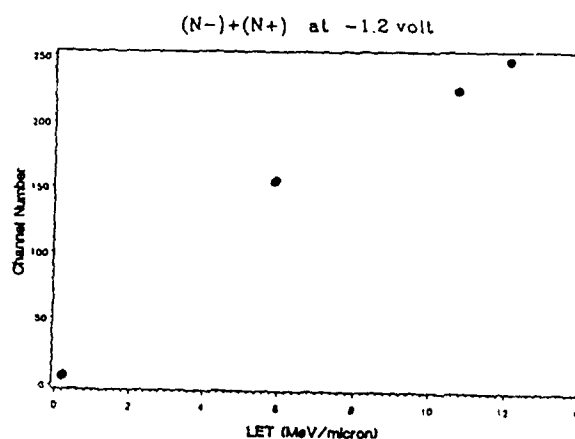

Fig. 7a

Fig. 7b

Fig. 8

Fig. 9

APPENDIX B

METHODS FOR CALCULATING SEU RATES FOR BIPOLAR AND NMOS CIRCUITS

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ABSTRACT

Computer codes developed at Clarkson for simulating charge generation by proton-induced nuclear reactions in well-defined silicon microstructures can be used to calculate SEU rates for specific devices when the critical charge and the dimensions of all SEU sensitive junctions on the device are known, provided one can estimate the contribution from externally-generated charge which enters the sensitive junction by drift and diffusion. Calculations for two important bipolar devices, the AMD 2901B bit slice and the Fairchild 93L422 RAM, for which the dimensions of the sensitive volumes were estimated from available heavy-ion test data, have been found to be in agreement with experimental data. Circuit data for the Intel 2164A, an alpha sensitive dRAM, was provided by the manufacturer. Calculations based on crude assumptions regarding which nuclear recoils and which alphas trigger upsets in the 2164A were found to agree with experimental data.

INTRODUCTION

Single-event upsets (SEUs) experienced by circuits traversing the inner radiation belts are primarily the result of nuclear reactions induced by protons trapped in the belts (1,2). In order to perform reliable calculations of SEU rates for specific devices, one must have a detailed knowledge of the natural proton environment, the ability to predict the pattern of charge generated by nuclear reactions as a function of incident proton energy, and, for each of the SEU sensitive junctions on the device, the dimensions of the junction and the critical charge that must be collected across that junction to trigger an upset. This paper describes how codes developed in our laboratory to predict charge generation in microstructures have been combined with simple assumptions regarding circuit response to calculate SEU rates in two different device types. The Intel 2164A was selected for calculations because both the required circuit information and consistent proton SEU cross section data is available (3). The 2901B bit slice was chosen because, in addition to proton data (4), heavy-ion SEU cross section measurements on the memory registers are available (5) which could be used to estimate critical charges and cross sectional areas for the sensitive junctions on the device, and the presence of a buried layer defines the thickness of the associated sensitive volume. The heavy-ion data available for the 93L422 (6) is less complete but good proton data exists (6). Upsets in the 2901B and the 93L422 bipolar devices have proven to be an important problem for many satellite systems.

CLARKSON SIMULATION CODES

Codes have been developed at Clarkson by Farrell and McNulty (7,8) which simulate the nuclear reaction and calculate the energy deposition within

parallelepipeds surrounding or close to the interaction. They are Monte-Carlo programs which choose the energy and trajectory of the incident proton according to the environment or accelerator exposure being simulated, randomize the locations of any nuclear reactions according to the inelastic cross section, and follow the standard cascade and evaporation models in choosing the identity, energy, and direction of secondary particles emerging from the cascade and evaporation stages of the interaction. For details of the nuclear physics behind the codes see Refs. 7-9 and especially Ref. 10. The computer follows each secondary particle to determine whether it intersects the sensitive volume defined by a parallelepiped as shown in Fig. 1. It then calculates the energy deposited in the sensitive volume by all the intersecting charged particles. The energy deposited can be converted to charge generated by dividing by 22 MeV/pC.
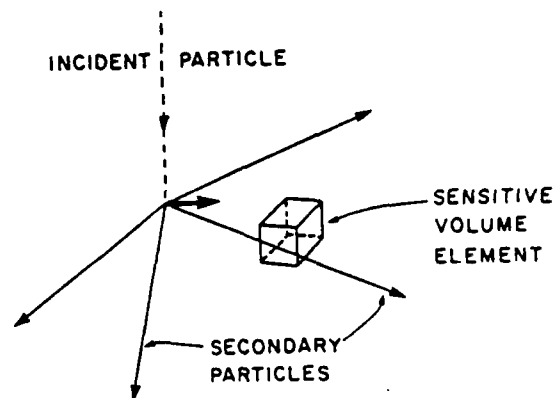

Fig. 1   Schematic of nuclear reaction relative to sensitive volume.

The codes have been tested extensively in silicon by comparison with pulse-height spectra of the charge collected in nuclear solid-state detectors with detector thicknesses ranging from 2 μm to 97 μm exposed in air to protons having incident energies ranging from 27 to 158 MeV. The codes are found to give good fits to the experimental data (7, 11). A typical comparison of simulated and measured integrated pulse-height spectra is shown for 125 MeV protons incident on a 2.5 micron thick detector in Fig. 2.
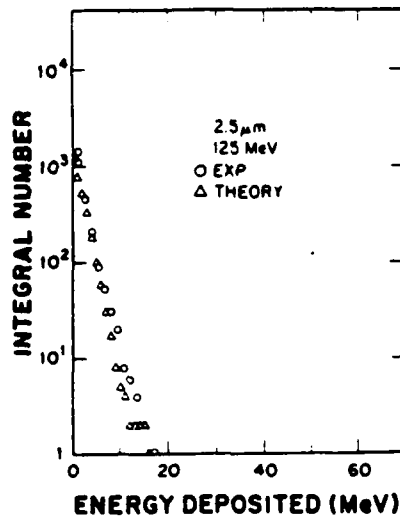
Fig. 2 Comparison of thoretical calculations of the number of events in which more than a certain energy is deposited versus that value of the energy deposited.

addressed during the exposure. Since only data for the unaddressed mode exist for both heavy ions and protons, we limit ourselves to this mode in what follows.
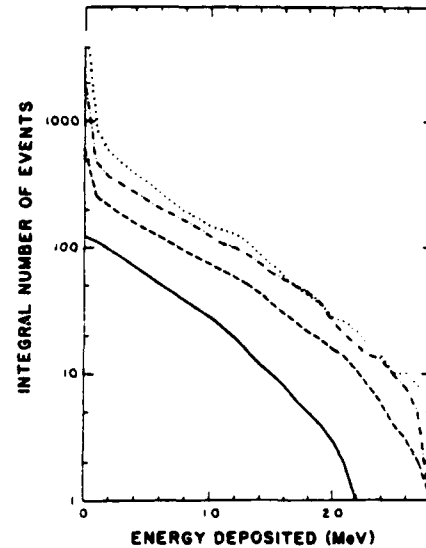

Fig. 3 Comparison of the simulated spectra of events in which more than a certain energy is deposited in a 1 μm cube of silicon embedded in different thicknesses of silicon surround but exposed to the same fluence of protons. Nuclear reactions can occur anywhere in the larger volume. Curves are drawn for external cubical volumes of 1 μm (solid),2 μm (dashed),4 μm (dot-dash),and 8 μm (dot).

User inputs include the number of protons incident on the exposed area, their energy spectra, and their angular distribution. Monoenergetic unidirectional beams arriving at normal incidence to the chip were used in all the comparisons with accelerator data described below. The user must also specify the dimensions of the larger parallelepiped in which nuclear reactions may be initiated and the location and dimensions of the smaller parallelepiped representing the sensitive volume within which the energy deposition is to be calculated.

Figure 3 compares the simulated energy deposition for the same small sensitive volume embedded in different thicknesses of surround. Significant contributions to the integrated energy-deposition spectra appear to only come from interactions that occur within 10 μm of the sensitive volume except at very small energy depositions. Low energy depositions are dominated by traversals of the sensitive volume by alphas and other light secondaries as evidenced by a sharp increase in events. This is consistent with our earlier conclusion that the recoiling nuclear fragment is the primary means of generating sufficient charge to generate an SEU in circuits that are insensitive to alphas (12). For circuits not sensitive to alpha strikes, the calculations can be shortened considerably by only considering nuclear interactions that occur within 10 μm or so of the sensitive volume (9).

BIPOLAR CIRCUITS

The AMD 2901B has been the subject of thorough studies of its SEU response to both protons and heavy ions at JPL. Zoutendyk, et al. (5) have shown that the 2901B exhibits different SEU cross sections depending upon whether the circuit element is being
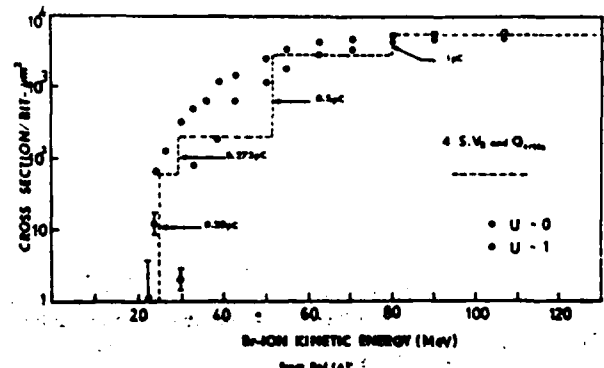

Fig. 4 SEU cross section versus kinetic energy of the incident bromine ion. Taken from Ref. 5. Dashed lines represent our attempt to fit their data by four sensitive volumes.
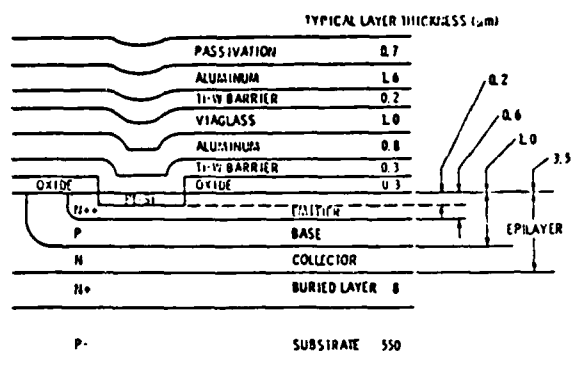
2901B (4). The cross-sectional areas that were obtained from Fig. 4 and used for these calculations are given in column 2 of Table 1. Column 1 represents the range of energy depositions in the 3 µm sensitive layer between threshold for that sensitive volume and threshold for the next larger one. Since the sensitive volumes are nested, the proton cross section for upsets at a given proton energy is taken to be the sum of the cross sections for depositing an energy between the threshold for that volume and the threshold for the next larger. These values are listed in Table 1.

Fig. 5 Schematic taken from Ref. 5 showing the thicknesses of the layers of a 2901B circuit element.

Table 1 (2901B)

E_{th} (Mev)	Cross Section(cm²) per Bit	Proton Energy (MeV)		
		56	130	590
3.3 — 5.9	60	2.3×10^{-12}	1.2×10^{-11}	1.5×10^{-11}
6.0 — 10.9	120	2.05×10^{-11}	1.21×10^{-10}	1.00×10^{-10}
11.0 — 21.9	3000	—	8.8×10^{-11}	5.56×10^{-10}
≥ 22	5000	—	—	7.6×10^{-11}
SEU CROSS SECTION(cm²) / DEVICE		2.33×10^{-11}	2.21×10^{-10}	8.35×10^{-10}

The SEU cross sections measured by Zoutendyk, et al. (5) are plotted as circles in Fig. 4 versus the energy of the incident bromine ion. Figure 5 is a schematic of the 2901B showing the thicknesses of the various layers of a circuit element. According to Ref. 5, the collected charge is the charge generated in the silicon layer between the level of the base-emitter junction and the top of the buried layer, a distance of 3um. Using the recipe and Figs. 6 and 7 from Ref. 5, the charge generated in this layer can be calculated for any bromine energy.

The dashed lines in Fig. 4 attempt to represent their measured cross sections by the lateral dimensions of four sensitive volumes - each having different critical charges. The cross sectional areas of the four volumes can be obtained from the ordinate of Fig. 4 and the critical charges can be determined from the abscissa. The thickness of all four are 3um. The critical charges determined for the four equivalent structures are given in Fig. 4 with arrows pointing to their corresponding thresholds. The presence of the buried layer presumably terminates any charge that might otherwise enter the sensitive volume by drift or diffusion from deeper in the substrate. The fact that the four sensitive volumes are nested must be taken into account in the proton calculations.

Calculations

The Clarkson codes were used to simulate the pulse-height spectra for exposure of the four sensitive volumes to protons incident at the three energies for which JPL proton data exist for the

Comparison between these calculated values and the experimental proton measurements on the 2901B taken from Ref. 4 is shown in Fig. 6. Circles represent simulated cross sections from this paper and the dashed curve connects the experimentally measured values at the same incident energies. The fit is excellent at the lower proton energies and reasonably good even at the highest energy.
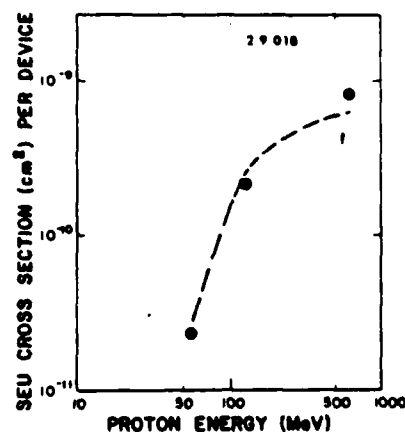

Fig. 6 Comparison of calculated SEU cross sections (circles) with measurements at the same incident proton energies for the 2901B. Dashed curve connects experimental points from Ref. 4.

A second bipolar device for which JPL heavy-ion and proton data exist is the FSC 93L422 RAM. Reference 6 reports a single measured threshold LET of 1.8 MeV cm^2/mg and a flat SEU cross section of 2000 µm^2 for ions having higher LETs. The sensitive volumes are arbitrarily assumed to have a thickness of 15 µm. A normally-incident particle with this threshold LET would deposit 6.2 MeV in a 15 µm layer of silicon. The Clarkson proton codes were used to calculate the cross section for depositing more than 6.2 MeV in a sensitive volume with lateral dimensions given by the SEU heavy-ion cross section and a thickness of 15 µm. Our calculations were not particularly sensitive to the thickness chosen for the sensitive volume. Figure 7 shows a comparison of our simulated cross sections (circles) calculated at a number of incident proton energies with the curve reported in Ref. 6 to best fit the JPL measured values. Again the agreement is excellent.
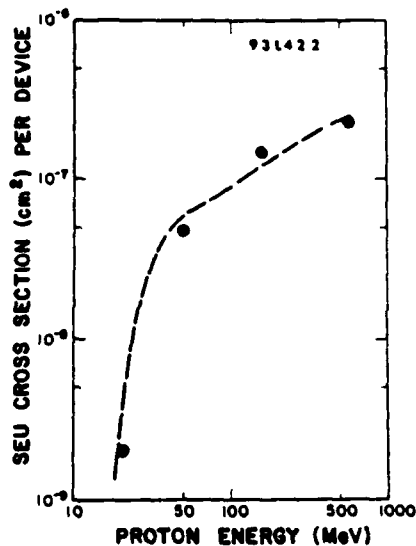

Fig. 7 Comparison of calculated SEU cross sections (circles) with with the best-fit curve from Ref. 6 for their 93L422 proton data.

NMOS DRAM

We assumed that SEUs in the Intel 2164A dRAM result from collecting a sufficient number of electrons to exceed the critical charge required for an error, 149 fC or 3.3 MeV. The lateral dimensions of the sensitive volume were taken to be those of the memory cell 8.5 µm x 16.5 µm and the thickness taken to be that of the depletion region under the node, 0.18 µm.

The collection of charge generated outside this sensitive volume through drift and diffusion must be considered. As a first attempt, we assumed that all recoiling residual nuclear fragments that traverse the sensitive volume trigger an upset if the recoil had a total kinetic energy equal to or greater than 3.3 MeV, i.e., we assumed all the charges generated

in the short recoils were collected through field-assisted drift. The number of such intersecting recoils resulting from simulated exposures to given fluences of protons are listed in row 5 of Table 2 for five different proton energies. The corresponding SEU cross sections for a 64K memory with alternating locations filled with ones and zeros are given in row 6.

The 2164A can be upset by alphas but the large critical charge suggest that only alphas that traverse the sensitive volume near the end of their range will trigger an upset. The high ionization levels needed to maintain field assisted drift along the trajectory are more likely to occur near the end of the track. The numbers of alphas in these simulations to emerge from nuclear reactions and strike the sensitive volume during the last 5 µm of its range are given in row 7 of Table 2 with the corresponding SEU cross sections per device given in row 8. The total proton cross section, i.e., the sum of the cross sections for recoil-induced and alpha-induced errors is given in the bottom row of Table 2.

Table 2 (Intel 2164A)

Proton Energy (MeV)	21	41	82	124	155
No. of Incident Protons ($\times 10^9$)	4.863	5.775	3.5	4.875	5.52
Fluence ($\times 10^{12}$ cm^{-2})	6.107	7.253	4.4	6.123	6.93
No. of Recoils Intersecting The Sensitive Volume (S.V.)	168	197	242	324	367
No. of Intersecting Recoils > 3.3 MeV	0	22	50	94	110
σ_r / Device ($\times 10^{-8}$ cm^2)	0	0.978	4.17	4.9	5.07
No. of Alphas Intersecting The S.V. (Ender)	5	162	117	192	244
σ_a / Device ($\times 10^{-8}$ cm^2)	0.26	7.14	8.49	10.035	11.36
$\sigma_r + \sigma_a$ ($\times 10^{-7}$ cm^2)	0.026	0.81	1.27	1.49	1.64

Experimental measurements to be described elsewhere (3) have been carried out at the same incident proton energies as used in the simulations. The advantage of these measurements over the earlier measurements on dRAMs (12,13) is that the 2164A, a part designed for military applications, exhibits far less variation in SEU cross section among devices than was true for those earlier commercial parts. The measured values presented below are averages of the cross sections measured for five parts where each measurement included over 100 errors. Figure 8 compares theory and experiment. The dashed lines connect points that represent the average measured cross section and the circles represent the simulated cross sections. The agreement is quite good except at 21 MeV. It is interesting to note that reducing the critical charge by about a factor of 2 would bring

the 21 MeV calculation into agreement without changing the other points significantly. Perhaps including the charge collected through thermal leakage between refreshes would improve the fit.
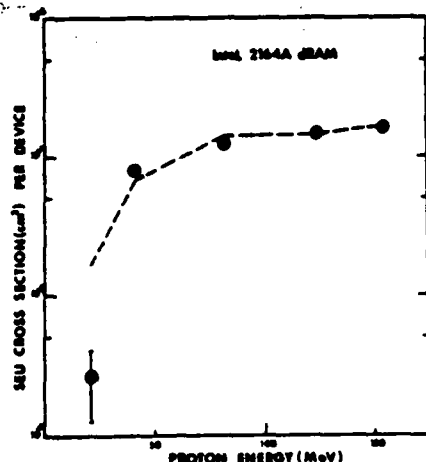

Fig. 8 Comparison of SEU cross sections obtained from simulations with measured values obtained at the same incident proton energies. The dashed curve connects points representing the average cross sections for five devices from Ref. 3.

CONCLUSIONS

The Clarkson codes developed for simulating charge generation pulse-height spectra can be used to calculate SEU cross sections for some devices with relatively simple assumptions. Further studies are needed to determine the extent to which the technique can be generalized. In particular, the dRAM calculations described above involve crude assumptions that may not work for circuits with smaller feature size and smaller critical charges. However, it is hoped that combining our codes with some of the sophisticated circuit models being developed by others will lead to comparable success for those devices which are not susceptible to the kind of simple assumptions attempted here.

The agreement found for the bipolar devices demonstrates that, for alpha insensitive devices, proton-induced upsets are primarily the result of the recoiling nuclear fragment and that heavy-ion data may be useful in predicting proton response and vice-versa. However, the short range of the nuclear recoil in proton interactions must be taken into account in making such correlations.

ACKNOWLEDGEMENTS

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APPENDIX C

COMPARISON OF SOFT ERRORS INDUCED BY HEAVY IONS AND PROTONS*

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ABSTRACT

Careful measurements of the SEU cross section versus the LET of the incident heavy ion were carried out on a single Intel 64K dRAM for which proton SEU data had been recently obtained in order to test whether a single set of modeling assumptions could provide fits to both data sets. The Intel 2164A 64k dRAM exhibited consistent cross-section measurements among devices tested, a high total-dose tolerance, and a proton SEU cross section that was unaffected by accumulated dose, making the device very suited for extended radiation studies. The heavy-ion cross section versus LET data was used as input to the CUPID code predictions of the proton-upset cross section versus incident proton energy. Observed agreement is consistent with the hypothesis that proton-induced upsets, even in alpha sensitive devices, are the result of recoiling nuclear fragments from inelastic nuclear interactions and the same basic mechanism is reponsible for both heavy ion and proton-induced upsets.

INTRODUCTION

Petersen et al (1) recently pointed out that no obvious correlation could be demonstrated between the relative sensitivity of devices to proton-induced single event upsets (SEUs) and heavy-ion-induced SEUs. On the other hand, our computer simulations of proton-induced energy-deposition events suggest that the charges generated in sensitive microvolumes having dimensions typical of silicon and GaAs devices would be dominated by the contribution of the nuclear recoil (2-5). We recently showed how heavy-ion data could be used to predict proton-induced upsets in two bipolar integrated circuits (6). In this paper we demonstrate that it is possible to accurately generate the proton cross sections for the Intel 2164A from analysis of the SEU cross section dependence on linear energy transfer (LET [MeV-cm^2/mg]) as obtained from heavy-ion exposures of the device.

The nuclear recoil is a heavy ion, therefore there should be a correlation between a device's sensitivity to nuclear reactions and the threshold LET measured for it with heavy ions. This does not mean that a collection of devices would necessarily rank order in sensitivity to protons in the same order as to heavy ions. The relative SEU sensitivity of

a device to protons of a given energy will depend on the dimensions of the sensitive volume. For very thin sensitive volumes, the event rate induced by protons should equal the rate at which nuclear recoils with more than a threshold LET traverse the sensitive volumes. For thicker volumes, i.e., where the smallest dimension becomes comparable to the typical range of a recoil, many recoils may have sufficient LET but not enough energy to trigger an SEU event or, even if they generate more than a critical charge within the sensitive volume, not enough of it reaches the depletion region to trigger an event.

The border between these two cases will depend on the threshold LET, the incident proton energy, the device geometry, and whether it is GaAs or silicon. Contributions from field-assisted drift and diffusion of charge generated outside the depletion region represent further complications which are partially taken into account in the simplest simulations by increasing the thickness of the sensitive volume a suitable distance beyond the that of the depletion region.

Providing a test of whether a single set of modeling assumptions can provide adequate fit to both proton and heavy-ion SEU cross sections requires that all data being compared be obtained using a single microchip with identical support circuitry. As far as possible, the modeling assumptions should be known beforehand, i.e., the device should be one for which the upset mechanisms are well understood with the relevant feature sizes and critical charges previously established. When the thickness of the sensitive volume used in proton simulation is not known, the ratio of the critical charge to the threshold LET measured with heavy ions should be used. The device should be capable of surviving the irradiations necessary to provide good statistics on soft errors. The Intel 2164A satisfied the above criteria and had the further advantages of exhibiting only small variations in SEU cross sections among devices tested and of not exhibiting significant changes in SEU cross section with increasing dose.

Proton exposures were done at Harvard University's Cyclotron using 21 to 155 MeV protons to characterize the device's proton cross section behavior and total dose response. Heavy-ion irradiations were done at the 88 inch Cyclotron at the University of California at Berkeley. The SEU

event cross sections were then combined with the
CUPID (Clarkson University Proton Interactions in
Devices) (2-6) simulations of proton exposures for
the Intel 2164A sensitive volume to predict the
proton response of the device. The results were
then compared with the experimentally observed pro-
ton cross sections and found to agree.

EXPERIMENTAL PROCEDURE

Experimental Apparatus

Test equipment for this experiment consisted
of a Zenith Z-100 microcomputer with one 64k dRAM
memory chip displaced from the mother board by a
three foot tether cable. The chip under test was
inserted in the socket at the end of this tether
and placed in the radiation beam. Initially loaded
with a test pattern of either ones and zeros
(proton) or all zeros (heavy ion), the test chip
was irradiated while a machine level program ex-
amined each memory location and recorded the time
and location of any errors discovered. Examination
of the information storage method on the Intel dRAM
indicated data was stored in a checkerboard pattern
as alternating blocks two rows wide and one column
long of true and complementary cells. This meant
loading either all zeros or alternating ones and
zeros had no effect on either the number of
sensitive cells or the pattern of their distribu-
tion. This record of the run was then stored on
disk at the end of the run for later examination.

To enable operation of the equipment, the
video monitor and keyboard were extended on cables
outside the beam cave. This enabled real time ob-
servation of errors and computer access without
continuously entering the beam cave.

Irradiation Facilities

Proton irradiations at incident energies from
21 to 155 Mev were carried out at the Cyclotron at
Harvard University while heavy-ion exposures were
carried out at the 88 inch Cyclotron at the
University of California at Berkeley. Table 1 shows
the species and energies of the particles used at
Berkeley.

Table 1   Species, energies, LET and range in
silicon used at the 88 inch Berkeley
cyclotron

SPECIES	ENERGY [MeV]	LET [MeV-cm^2/mg]	Range [microns]
Krypton	210	42.37	28.43
Argon	110	16.99	28.0
Neon	58	6.81	30.2
Carbon	380	0.53	1810.0
Oxygen	424	1.07	969.0
Helium	11.8	0.35	88.75

The Intel 2164A

The principal SEU-sensitive structure in the
2164A is the storage cell, an inversion layer formed
under the source electrode of an FET as shown in Fig.
1. The area of the storage cell in the 2164A is 140
square microns and estimates of the width of the de-
pletion region and the critical charge needed for an
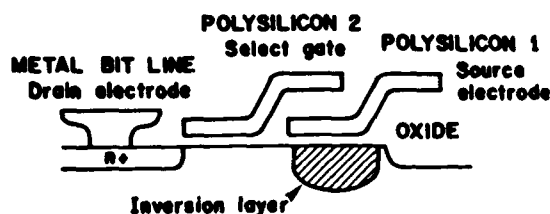upset are 0.18 microns and 149 fC, respectively (7).

Fig. 1   Storage cell diagram of the Intel 2164A

To obtain a good cross section versus LET re-
sponse, it was necessary to screen each heavy-ion run
for shadowing, row hits and multiple errors. Shadow-
ing occurs at large angles of incidence in ex-
periments where the ceramic edge of the chip package
walls can shield a portion of memory from heavy-ion
irradiation. Row hits are a series of errors that
occur along a certain row of the device. They are
believed to result from a single hit in a sense
amplifier, dummy cell or bit line. Multiple errors
occur in adjacent cells during the same checking per-
iod. They appear to be caused by the charge generated
by the passage of one high LET particle being col-
lected in more than one memory location. A program
was written to map errors according to their physical
locations on the chip and tested by optical
microscope beams. Figure 2 shows the errors on such
a map resulting from a narrow light beam incident on
a chip initially loaded with alternate ones and
zeros. The spot could be enlarged or focused until
only one storage cell was triggered. Moving the
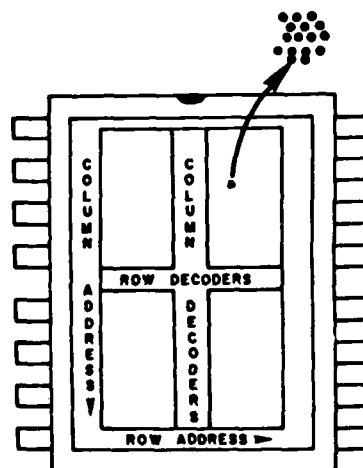microscope stage allowed us to probe all locations on
the chip.

Fig. 2   Errors due to photoionization by light beam
on Intel 2164A. Checkerboard appearance is
due to the chip architecture storing in-
formation in true and complementary format.

Individual errors induced by proton and heavy-ion irradiation produce small dots on such a row-column address map as shown in Fig. 3. The effects of shadowing are evidenced in Fig. 3 by an absence of errors from a large area on the right. Figure 3 shows that only 75% of the memory cells were exposed to the beam at 60 degrees incidence.

Close inspection of Fig. 3 shows frequent doublets which subsequent analysis showed to correspond to double-error events. Using information gathered from such mapping, the computer identifies simultaneous upsets which form a single event. A multiple error event is counted as one event in calculating event cross sections.
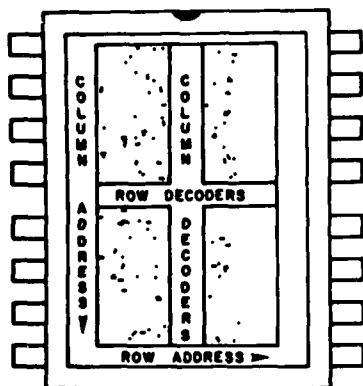
Fig. 3   Errors due to irradiation by heavy ions at 60 degrees incidence. The effects of shadowing and multiple error hits can be seen.

RESULTS

Proton Irradiations

Figure 4 compares the SEU cross section versus incident proton energy for seven Intel 2164A chips. The cross section shows little variation, even though the data is from two runs performed in two different months. In Fig. 4 and following figures the data points represent measurements with about 10% standard deviation. The variation appears somewhat larger at 21 MeV, but small fluctuations in the critical charge for different cells on the device and the energy spread in the proton beam introduced by the thick degraders used to obtain low energy beams could account for this small variation. The cross sections in Figs. 4 through 7 are expressed in cm^2/device.

Several devices were tested for total-dose dependence of the SEU cross section with 155 and 40 MeV protons. The cross section is plotted versus dose received for 155 and 40 MeV incident protons in Figs. 5 and 6 respectively. In both cases the run was terminated by chip dose failure. Somewhat larger fluctuations were observed for the chip exposed to 40 MeV protons, just before failure. Still, no systematic increase or decrease in SEU cross section was observed at either energy. Little change in the cross section was observed at 155 MeV as the dose received increased.
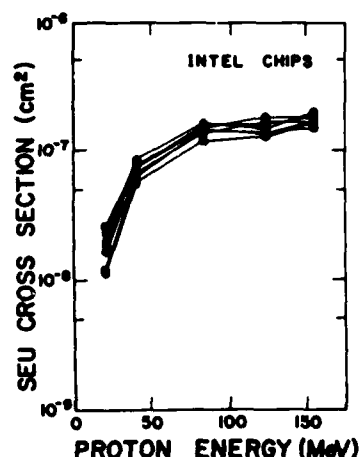
Fig. 4   SEU cross section versus proton energy for several Intel 2164A.
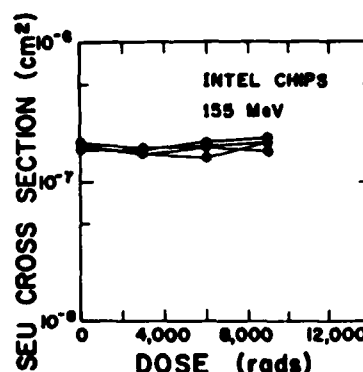
Fig. 5   SEU cross section versus total dose for Intel 2164A devices. Run was done with 155 MeV protons.
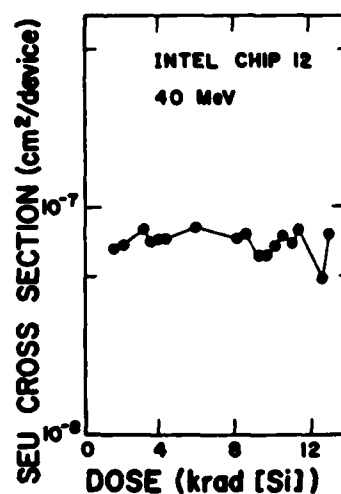

Fig. 6   SEU cross section versus total dose for an Intel 2164A device. Run was done with 40 MeV protons.

In addition to a consistent cross-section response, the Intel 2164A dRAM exhibited a high total-dose tolerance compared to other 64k dRAMs. Measurements of a total dose to failure of 13.4 Krads(Si) with protons were in agreement with earlier gamma ray (8) studies. Similar experiments using protons were performed using several TI 4164 commercial dRAMs as a comparison, and it was found that these devices survived about 3.5 krads(Si). Table 2 summarizes the results of the proton total dose measurements on the Intel and TI devices.

Table 2   Total dose to failure for Intel 2164A and TI devices using 40 and 155 MeV protons and gamma rays.

DEVICE No.	TOTAL DOSE [Krad(Si)]	IRRADIATION
TI #1	4.1	155 MeV proton
TI #2	3.5	''
TI #3	3.5	''
Intel #1	13.3	''
Intel #2	13.8	''
Intel #3	12.8	''
Intel #4	14.6	''
Intel #5	12.9	''
Intel #12	13.2	40 MeV proton
Intel (10 devices)	13.2+/-1.2	gamma (ref. 8)

The proton induced SEU measurements summarizied in Fig. 4 were carried out on devices complete with lids. Device #7, chosen for heavy-ion as well as proton irradiations, had its lid removed before both the proton and heavy ion measurements. Figure 7 compares the lid-off proton data obtained with this chip with a curve representing the average proton SEU cross sections for the seven lidded chips plotted in Fig. 4. The difference between the two results is only seen at the lowest two energies, 21 and 41 MeV. The differences there are consistent with the fact that the incident protons arrive at the sensitive structures of chip #7 with 8.5 and 5 MeV higher energies because of the energy lost in traversing the lids of the other devices.

Heavy-Ion Irradiations

Chip #7 was thoroughly characterized using heavy ions at the Berkeley facility, with two other devices examined for comparison. The initial pattern in memory was all zeros. In Fig. 8 the cross section obtained from the ratio of the total errors detected to the fluence of incident particles is plotted versus the LET of the incident particles with appropriate geometric corrections for angle of incidence. The data plateaus significantly above the geometric cross section and exhibits large variations in cross section at different LET values.

The runs were then examined for shadowing and multiple-error occurrences. Multiple-error events took the form of doubles, triples, and what we called ''row fails'', i.e. long strings of upsets in the same row. Shadowing and row fails are easy to identify on topological bit maps produced by knowing the address-descrambling logic of the device. However, more information is needed to identify doubles and triples. To be identified as a multiple-error event, the errors must occur sufficiently near one another and must occur in the same checking cycle, therefore location and time need to be recorded. This method works best when the flux of incident particles
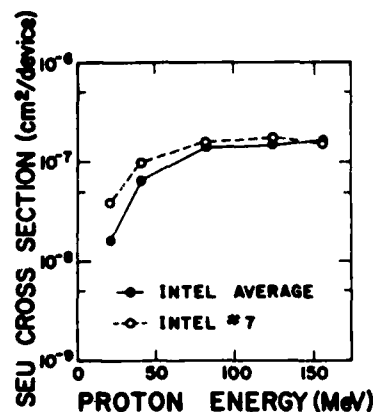

Fig. 7   SEU cross section versus proton energy for the average Intel and lid-off device. The difference at low energy is attributable to energy loss across the lid.
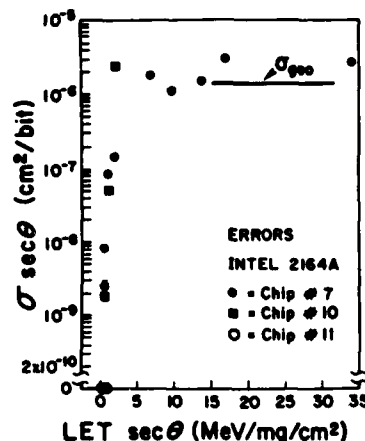

Fig. 8   Uncorrected cross section versus LET response of the Intel device.

is kept low, thus limiting possible coincident single hits that could be mistaken for a multiple error event. The number of multiple errors observed on our heavy-ion runs was much higher than could be explained statistically as random coincidences. It would also be useful to note here that no row fails and only a small number of multiple error events were observed with the proton irradiations of the Intel devices.

Figure 9 shows the event cross sections for single, double, and triple error events as determined from the ratio of the number of such events to the incident fluence. This is an event cross section, a double-error event produces two errors while a triple error event produces three errors, but each still counts as a single event in the cross section. Double events are obviously a major factor for high-LET particles. The cross section for both double and triple errors rises with LET with the cross section for double errors apparently tracking the single error cross section. The triples have a different dependence on LET than the singles or doubles.
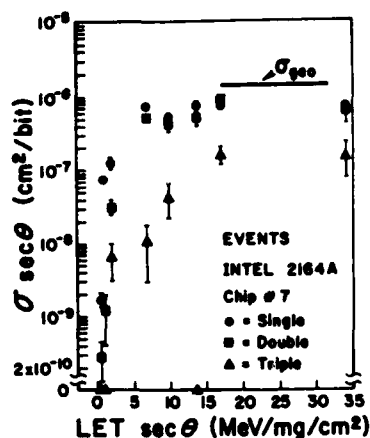
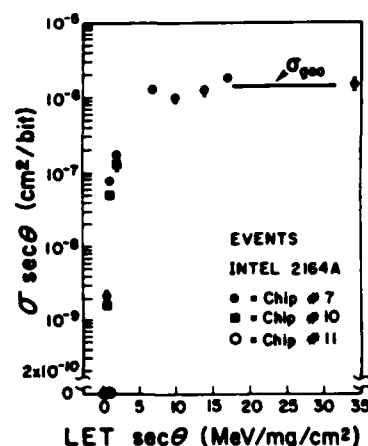Fig. 9   Cross section versus LET characteristics for Intel #7 for single, double and triple events.

Fig. 10   Adjusted event cross section versus LET response for three Intel devices. Here multiple events and shadowing are accounted for.

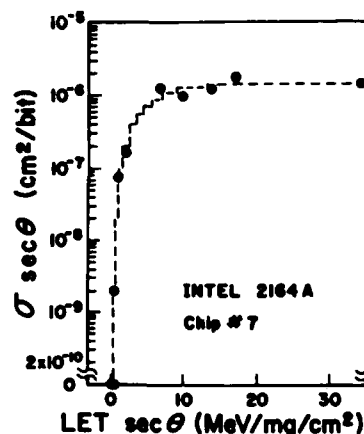Analysis of the memory cells experiencing multiple errors by placing the errors on an interleaving cell pattern that simulates the actual interleaving pattern of the memory cell indicates that the main mechanism is charge sharing from a single track by nearest neighbor cells. This is the subject of another study to be published elsewhere (9).

For comparison of the total SEU event cross sections with theory (10), multiple errors induced by a single particle should be identified and only counted once. Figure 10 shows the cross section for SEU events plotted versus the incident particle's LET where multiple-error events are counted only once. The SEU cross section is seen to plateau at about the geometric cross section as determined by the area of the storage cell. This is in agreement with the hypothesis that upsets are induced by heavy-ion traversals of the storage cell (10).

Fig. 11   Adjusted event cross section versus LET for device #7 only. Dashed line represents the cross section versus LET values used in the CUPID codes for calculating proton cross sections.

CUPID Calculations

The CUPID computer codes were developed to calculate the energy deposited in a slab of material as the result of inelastic nuclear interactions due to protons. The sensitive volume is embedded in a larger surrounding volume and a Monte-Carlo simulation is carried out for protons incident upon the larger volume at a given energy and angle. The energies, ranges and directions of secondaries and nuclear recoils resulting from proton-induced interactions anywhere in the larger volume are calculated and the charged particles followed to see if they intersect the smaller (sensitive) volume. The energy deposited in the sensitive volume by each particle that crosses it is then calculated.

Simulations of the proton exposures for the Intel 2164A dRAM used a sensitive volume of 140 square microns area with a thickness of 3.37 microns embedded in a larger silicon surround. The thickness was calculated from the ratio of the measured threshold LET and the critical charge of the device given by the manufacturer (7). The threshold LET corresponding to 50% of plateau is estimated from

Fig. 10 to be 4.3 MeV/mg/cm^2 and the critical charge was available from the manufacturer and is 149 fC or 3.3 MeV. The experimental heavy-ion cross-section data was then used in the codes to simulate the device's response to nuclear recoils; this was done by breaking a smooth curve through the data points in Fig. 10 into 10 steps to predict the device's response to nuclear recoils of various LET values. The dashed line in Fig. 11 shows how the approximation to the experimental data was done.

Comparisons of this calculation with experimental data obtained with protons on Intel chip #7, exposed without a lid, are shown in Fig. 12. They appear to be in excellent agreement at all proton energies.
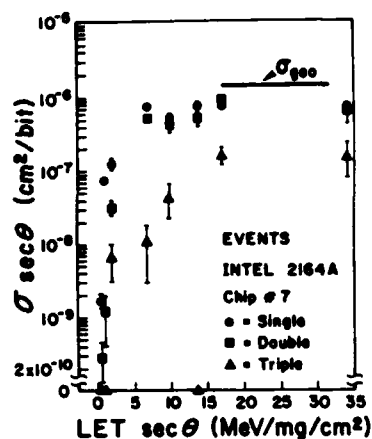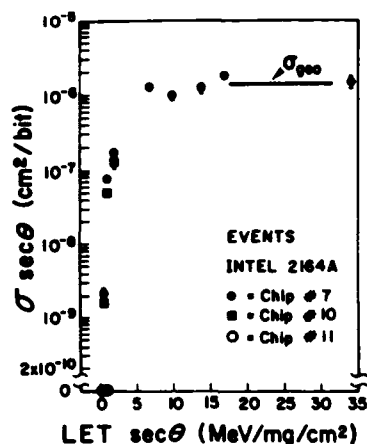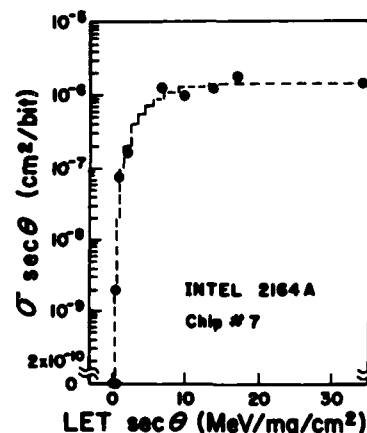
Fig. 9 Cross section versus LET characteristics for Intel #7 for single, double and triple events.

Fig. 10 Adjusted event cross section versus LET response for three Intel devices. Here multiple events and shadowing are accounted for.

Analysis of the memory cells experiencing multiple errors by placing the errors on an interleaving cell pattern that simulates the actual interleaving pattern of the memory cell indicates that the main mechanism is charge sharing from a single track by nearest neighbor cells. This is the subject of another study to be published elsewhere (9).

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Fig. 11 Adjusted event cross section versus LET for device #7 only. Dashed line represents the cross section versus LET values used in the CUPID codes for calculating proton cross sections.

Fig. 10 to be 4.3 MeV/mg/cm^2 and the critical charge was available from the manufacturer and is 149 fC or 3.3 MeV. The experimental heavy-ion cross-section data was then used in the codes to simulate the device's response to nuclear recoils; this was done by breaking a smooth curve through the data points in Fig. 10 into 10 steps to predict the device's response to nuclear recoils of various LET values. The dashed line in Fig. 11 shows how the approximation to the experimental data was done.

Comparisons of this calculation with experimental data obtained with protons on Intel chip #7, exposed without a lid, are shown in Fig. 12. They appear to be in excellent agreement at all proton energies.
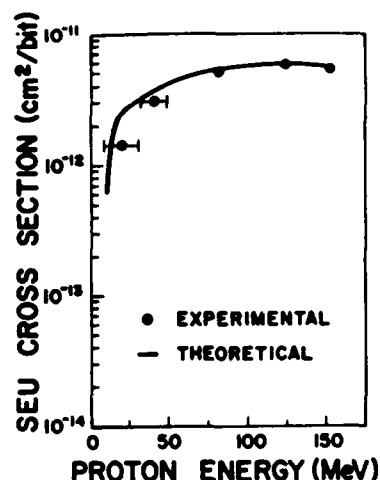
Fig. 12 Comparison of proton cross sections calculated using the experimental heavy-ion spectrum (curve) with the experimentally measured proton cross-sections (circles) obtained from Intel #7.

CONCLUSIONS

The results for a single Intel 2164A dRAM seems to provide evidence that both the proton and heavy-ion SEU response can be modeled under a single set of assumptions, governed by a *single underlying* mechanism. This agrees with our previous results for bipolar devices. We have not yet attempted such a comparison for CMOS devices.

Calculations simulating nuclear reactions and the passage of secondary particles through a sensitive volume combined with experimental heavy-ion SEU cross section versus LET data, appear to give excellent agreement with experimental proton runs on the same device. A key feature in this calculation is starting with a good heavy-ion cross-section curve, which in turn requires close examination of the errors generated in order to check and correct for shadowing and multiple-error events.

This work seems to indicate that a single mechanism is responsible for both proton and heavy ion upsets and that models which make relatively crude assumptions regarding extending the depth of the sensitive volume to take into account the funneling and diffusion of charge into the depletion region appear to be adequate at least for this simple structure. It also follows that the ratio of the critical charge determined from electrical measurements to the threshold LET determined by heavy-ion measurements gives a reasonable estimate of the thickness of the sensitive volume. A comparison of this value of the thickness with calculated values based on doping levels and electrical measurements is in preperation. The technique used here predicted the proton upset cross sections versus incident proton energy with reasonable accuracy for a small sample of different device types (6) but more testing on other types is necessary to confirm any general usefulness of the technique.

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TUTORIAL

FUNDAMENTALS of SINGLE EVENT PHENOMENA

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dna

Defense Nuclear Agency

TUTORIAL OUTLINE

* DESCRIPTION OF SINGLE EVENT PHENOMENA

* SENSITIVE MICROSTRUCTURES

* TESTING PROCEDURES

* PREDICTING RATES IN SPACE

* SAMPLE CALCULATIONS

* HARDENING TECHNIQUES

dna

SINGLE EVENT RADIATION EFFECTS

- SINGLE EVENT LATCHUP
  - Discovered: 1979, Kolasinski, et.al.
  - Analyzed: 1981, Pickel
- SCR ACTION IN PNPN PATH
  - Initiated by Single Particle
  - Device Draws Large Current
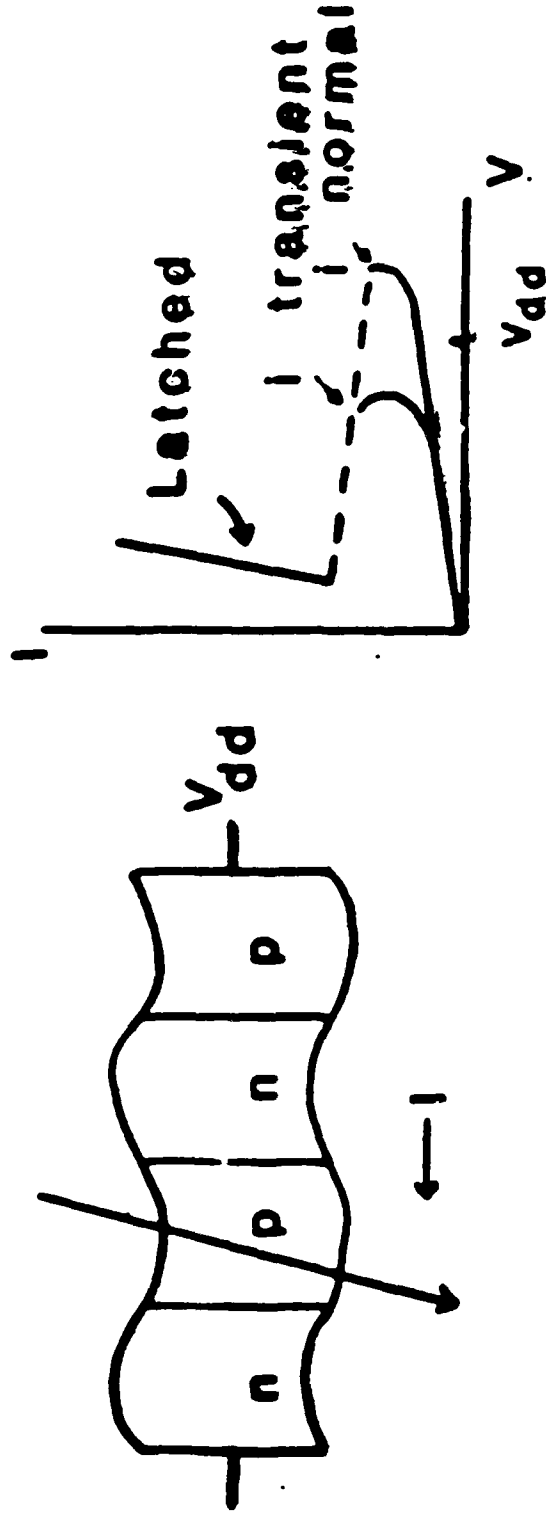
SINGLE EVENT PHENOMENA

INDUCED BY INDIVIDUAL IONS OR INTERACTIONS

TYPES:

SOFT

SINGLE EVENT UPSETS
LATCHUP

HARD

PERMANENT DAMAGE TO ONE ELEMENT

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SINGLE EVENT UPSETS

* CHANGE IN ELECTRICAL STATE OF A MICROSTRUCTURE

* BIT UPSETS IN MEMORY

* INCORRECT ROUTING IN CPU
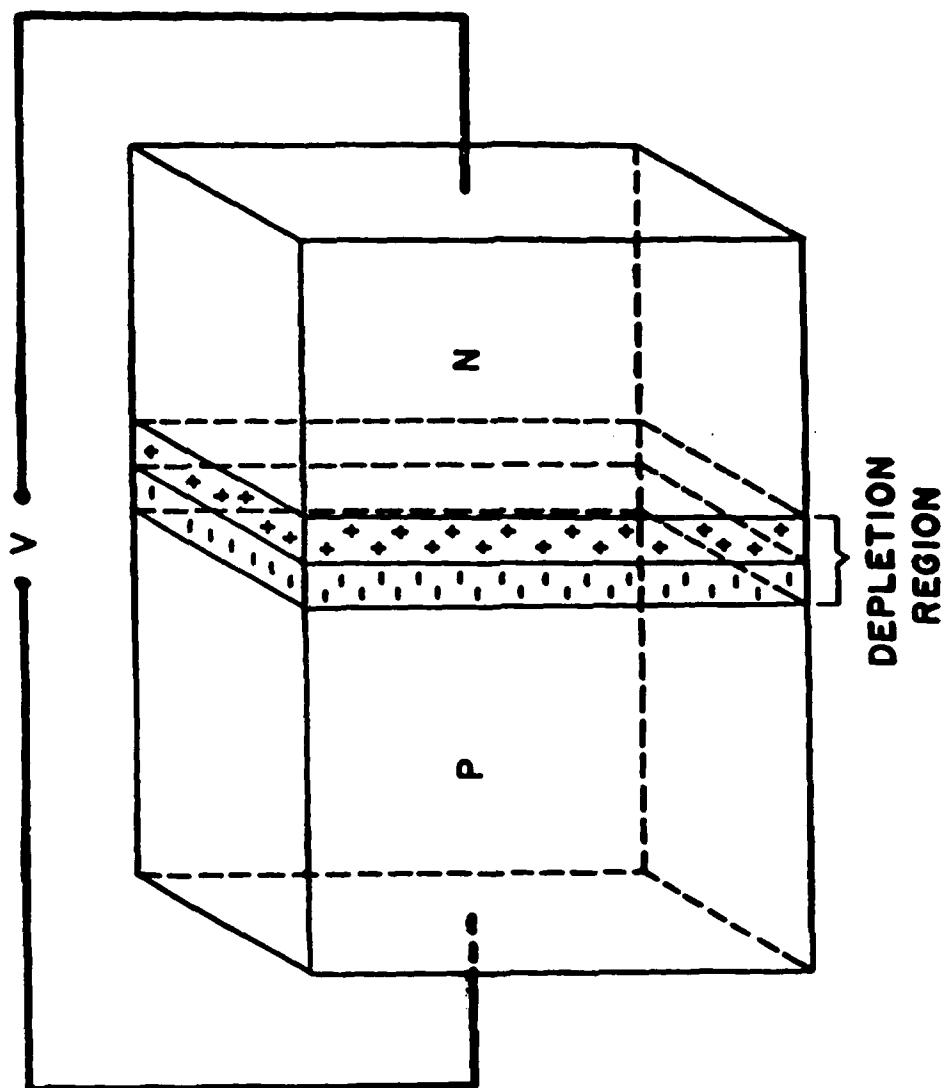
V

N

P

DEPLETION
REGION

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V_{BE} B V_{BC}

E

E N P N C

BASE ⌐ DEPLETION REGION

V

P N

DEPLETION
REGION

SCHOTTKY DIODE
FORMED AT
JUNCTION

B (OV) E (OV) N++ EMITTER C (+V)

N+

P+ BASE

N COLLECTOR

N+ BURIED LAYER
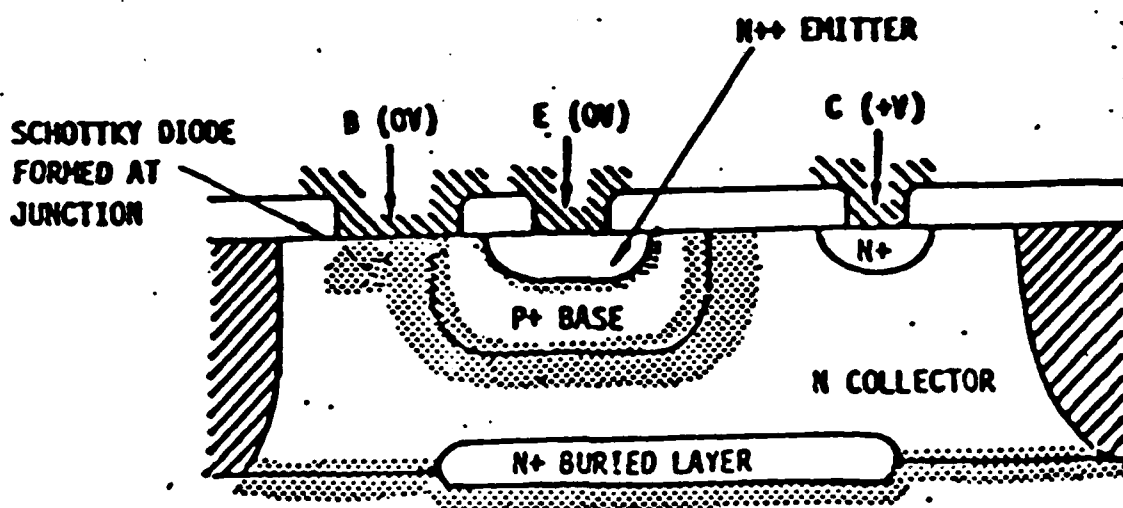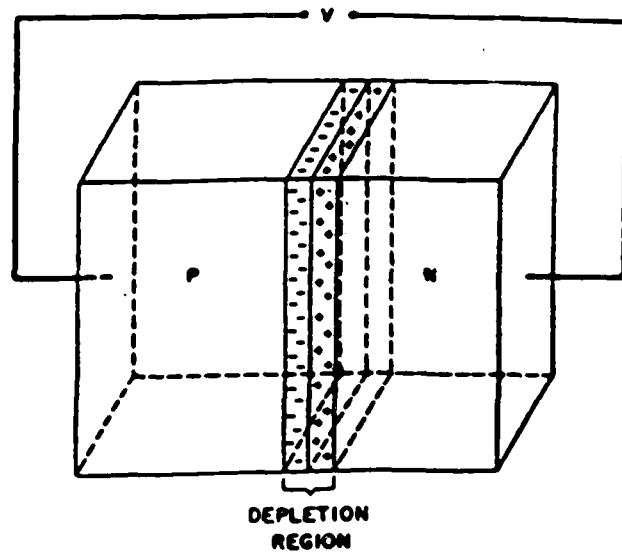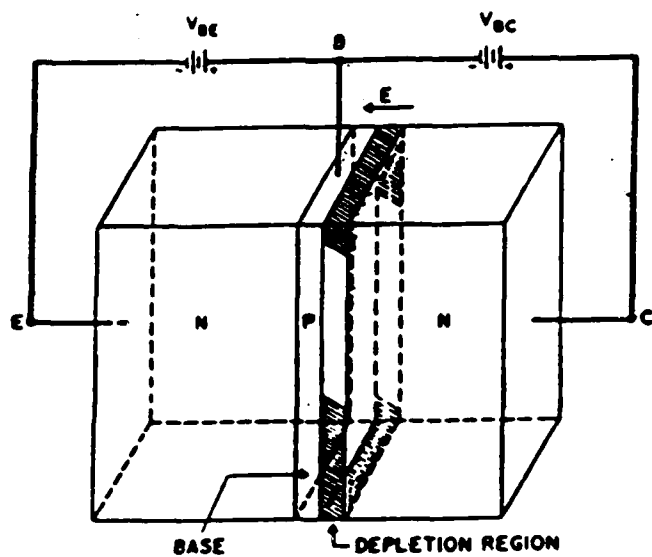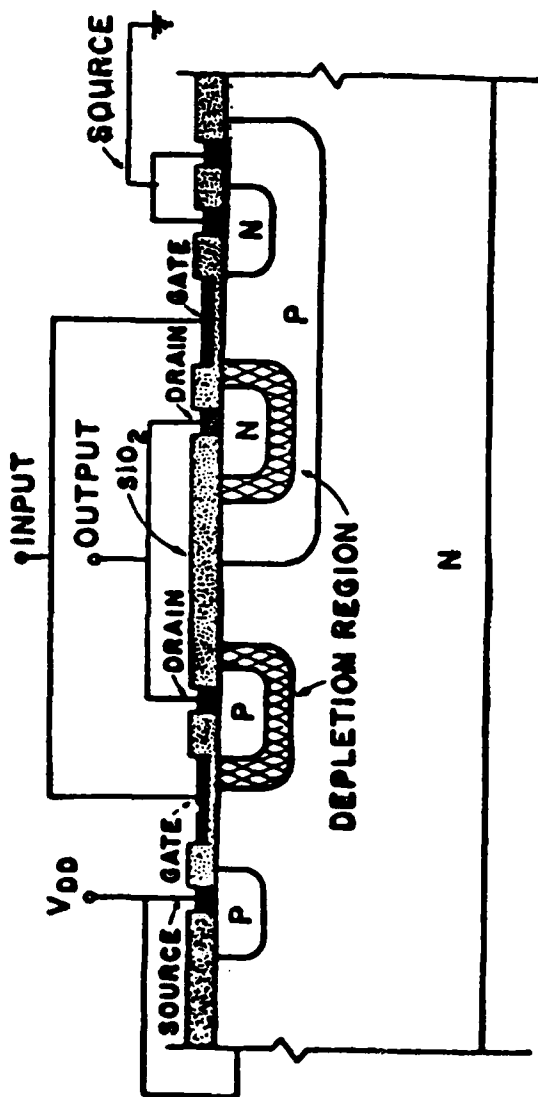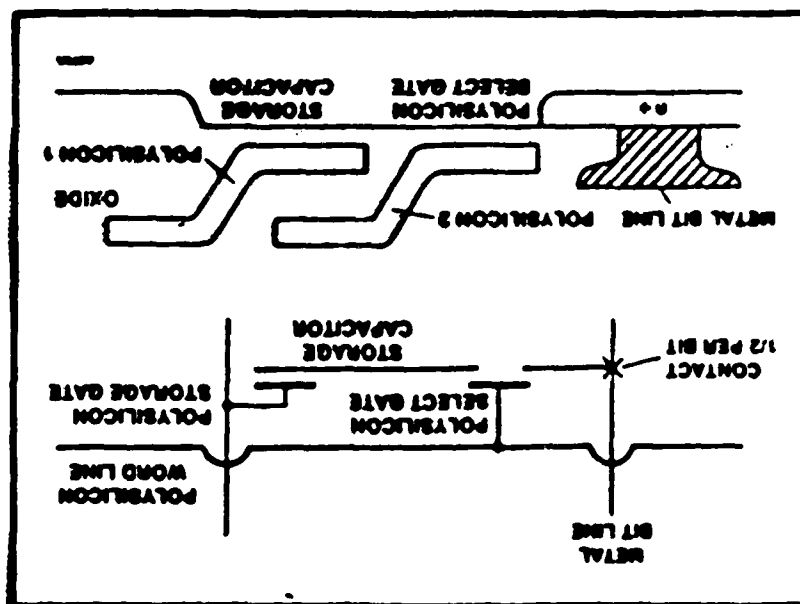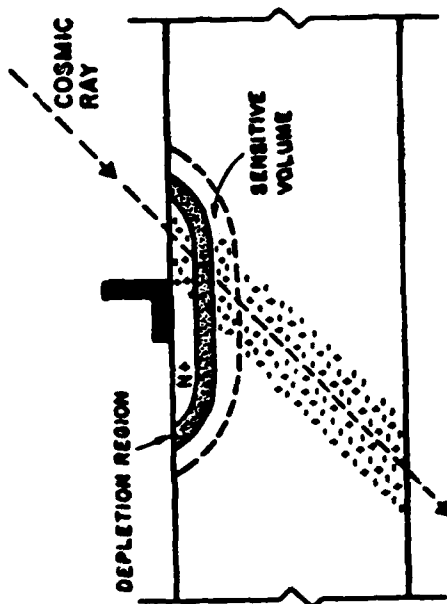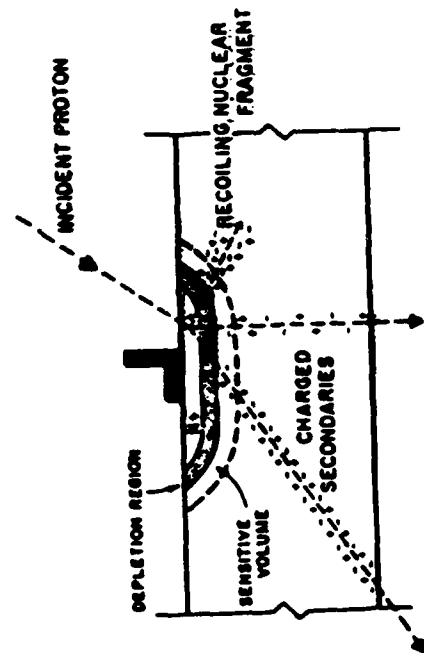
GENERATION AND COLLECTION OF CHARGE

THREE COMPONENTS

* FIELD ASSISTED DRIFT – DEPLETION LAYER

* FIELD ASSISTED DRIFT – FUNNELING

* DIFFUSION

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CALCULATION OF COSMIC RAY UPSET RATES

1. **NEED NUMBER OF OCCASIONS** $Q > Q_c$

   - Q_c = **CRITICAL CHARGE, FROM MODELS OR EXPERIMENT**

2. **Q DEPENDS ON ENERGY LOSS OF PARTICLE**

   - $Q \sim \dfrac{dE}{dX} \times dl$

   - **DEPENDS ON PATH LENGTH** dl
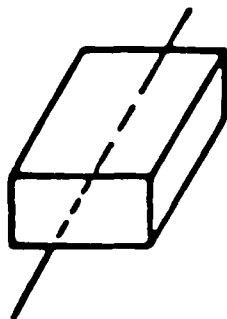
3. **RATE DEPENDS ON SIZE OF DEVICE**
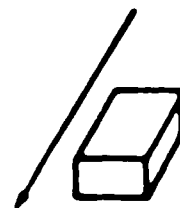
4. **COMBINE — TARGET SIZE**
   - **— LET DISTRIBUTION**
   - **— PATH LENGTH DISTRIBUTION**
   - **— CRITICAL CHARGE**

HEAVY ION UPSET MEASUREMENTS
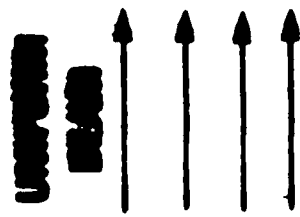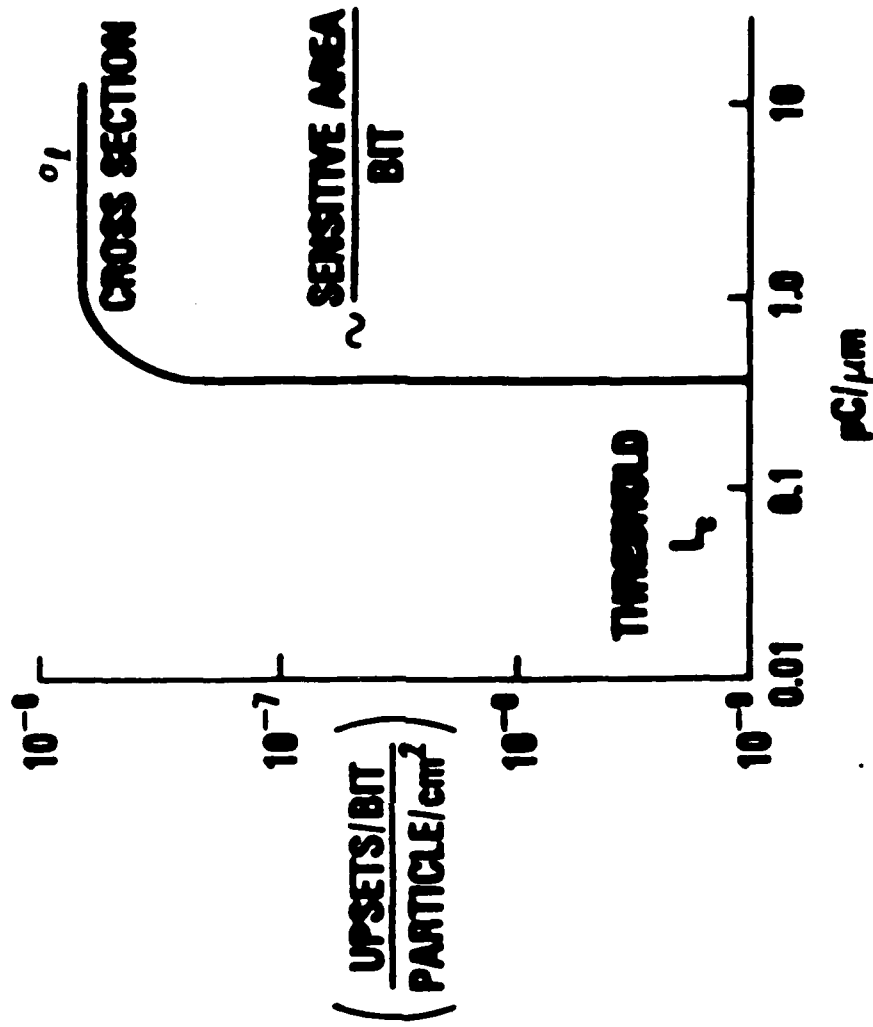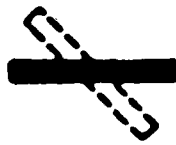
93 L422

SEU CROSS SECTION (cm^2) PER DEVICE vs PROTON ENERGY (MeV)

Ref. (5)

$\sigma = 2 \times 10^{-2} cm^2/Device$

LET = 1.8 MeV-cm^2/mg

$t = 15 \mu m$

TOTAL ERRORS = 83

TI-4164   TI-B5D.DAT

SENSE AMPS / COLUMN DECODERS

ROW DECODERS

①

(0,0)

Triple

Orgin

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Defense Nuclear Agency

MROW/MCOL =   79   54.   TI-4164   TI-B5D.DAT

C->

R

|
|
|
v

?

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σ secθ (cm^2/bit)

10^{-5}

10^{-6}

10^{-7}

10^{-8}

10^{-9}

2×10^{-10}
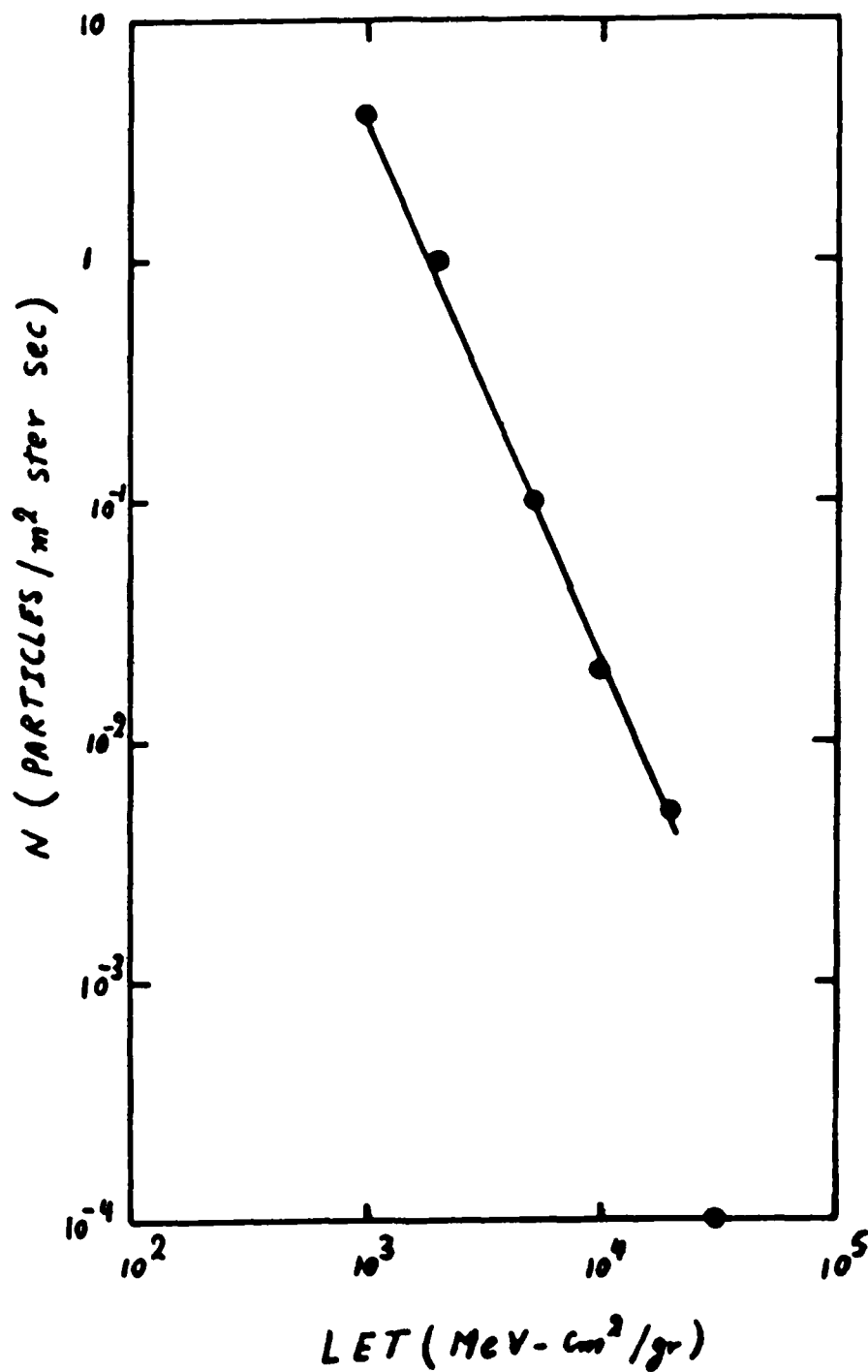
0

0   10   20   30

LET secθ (MeV/mg/cm^2)
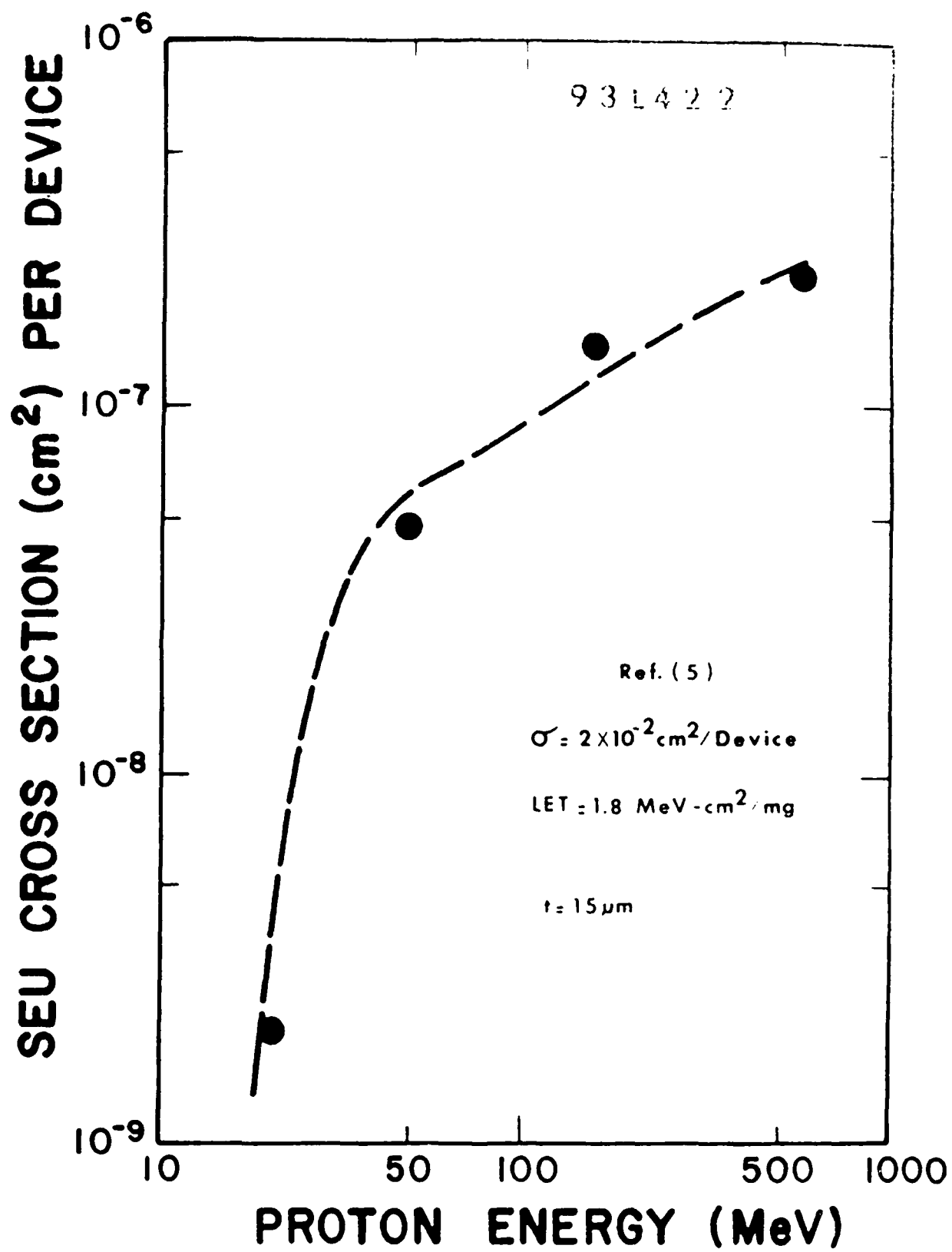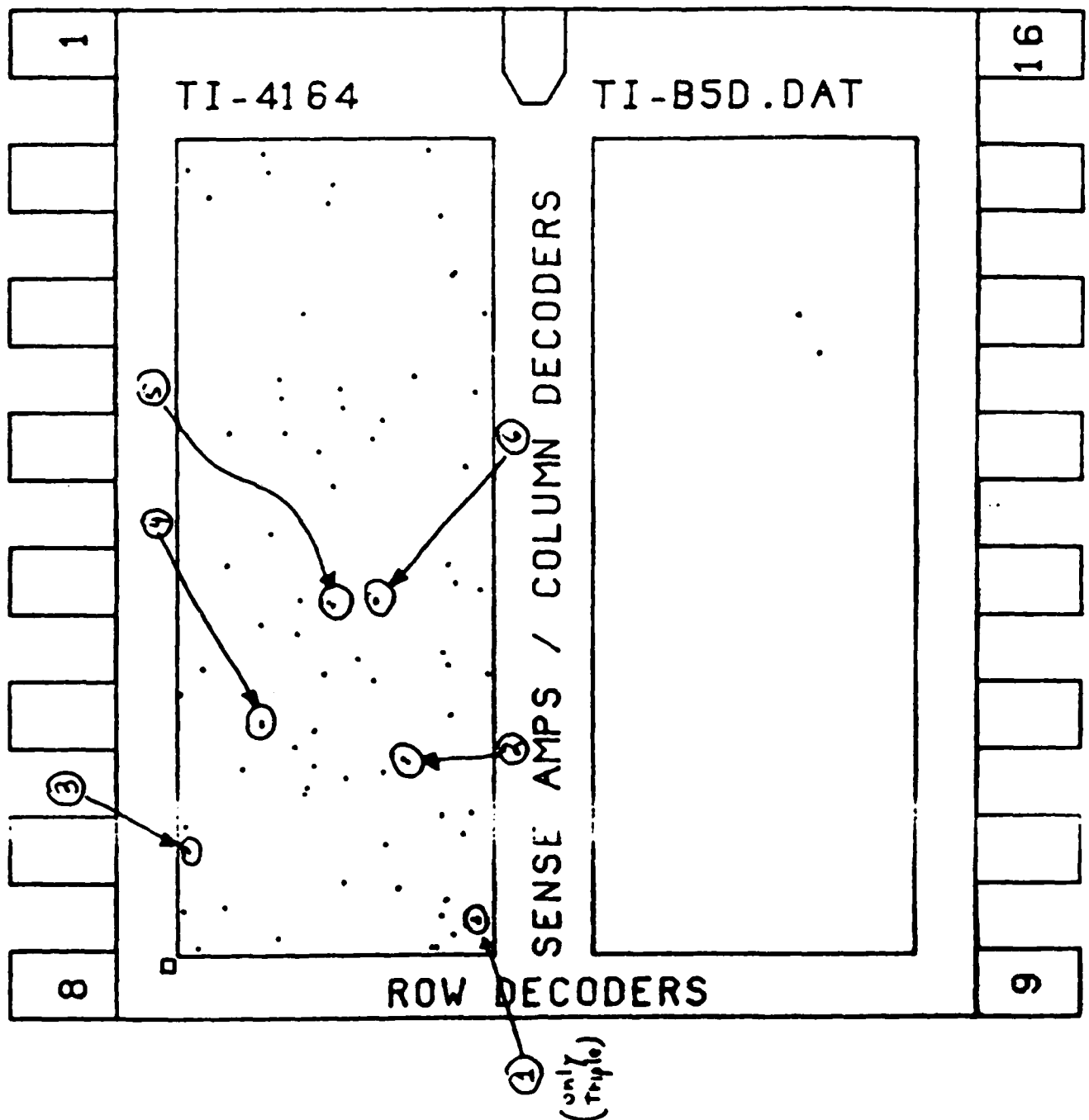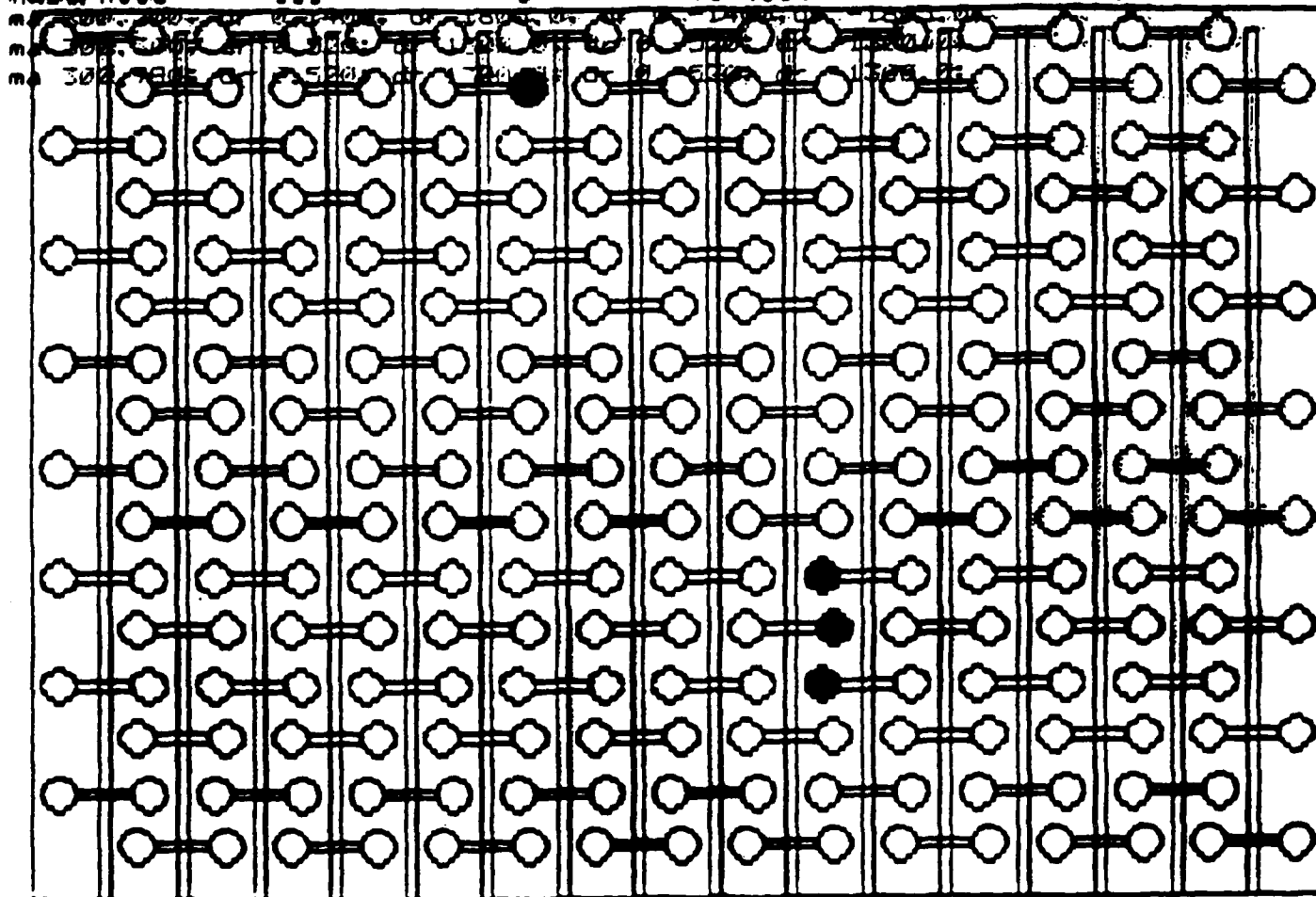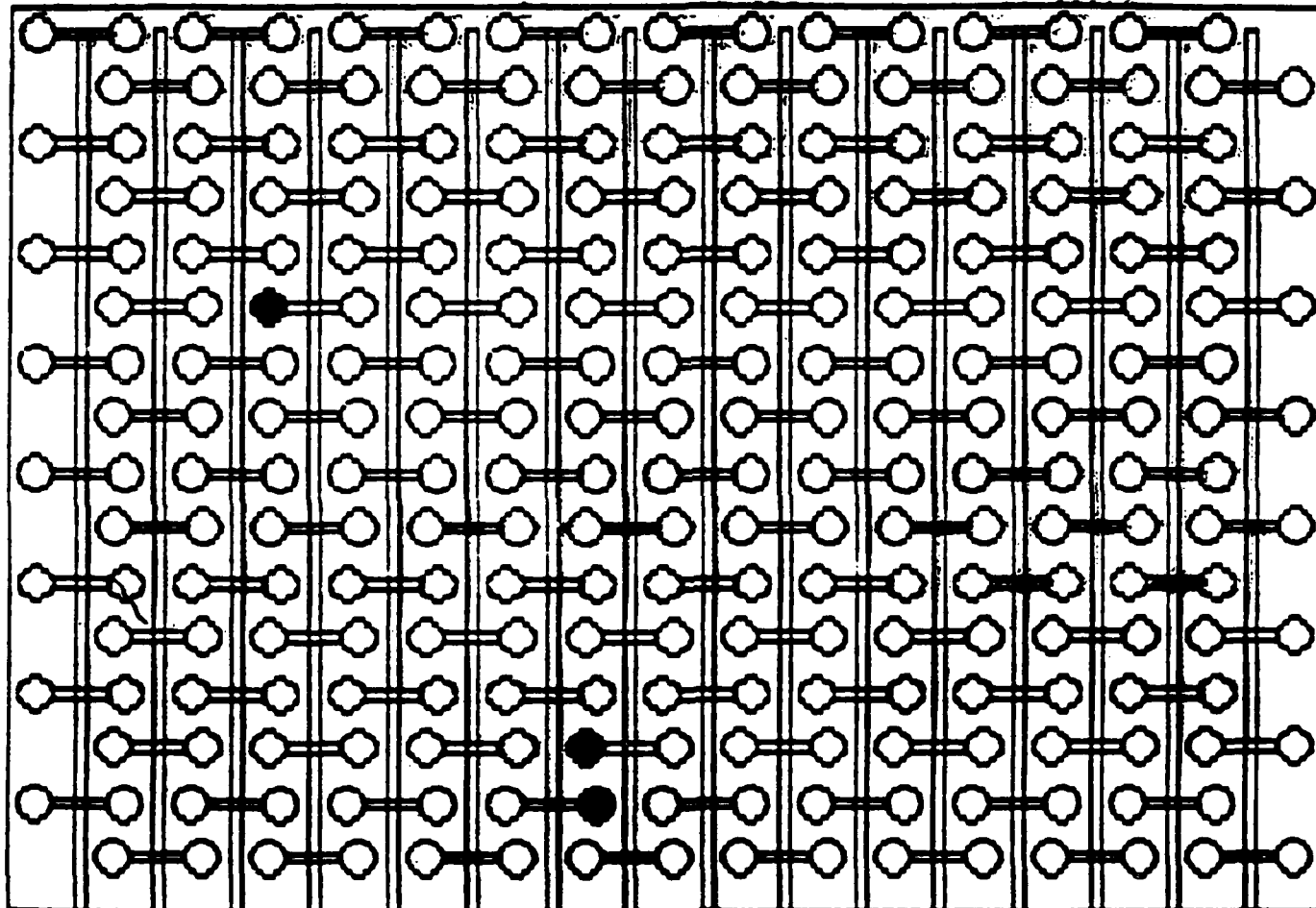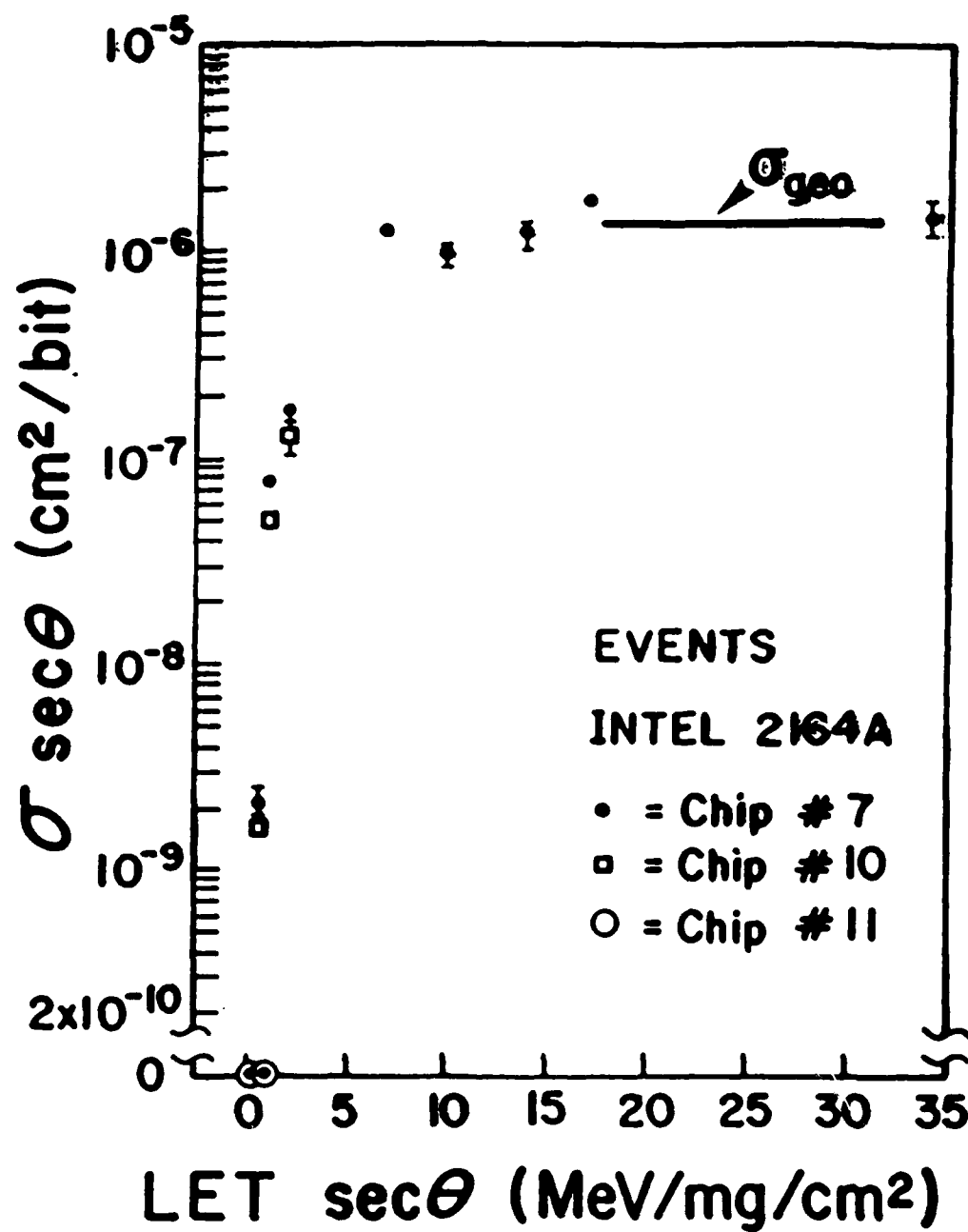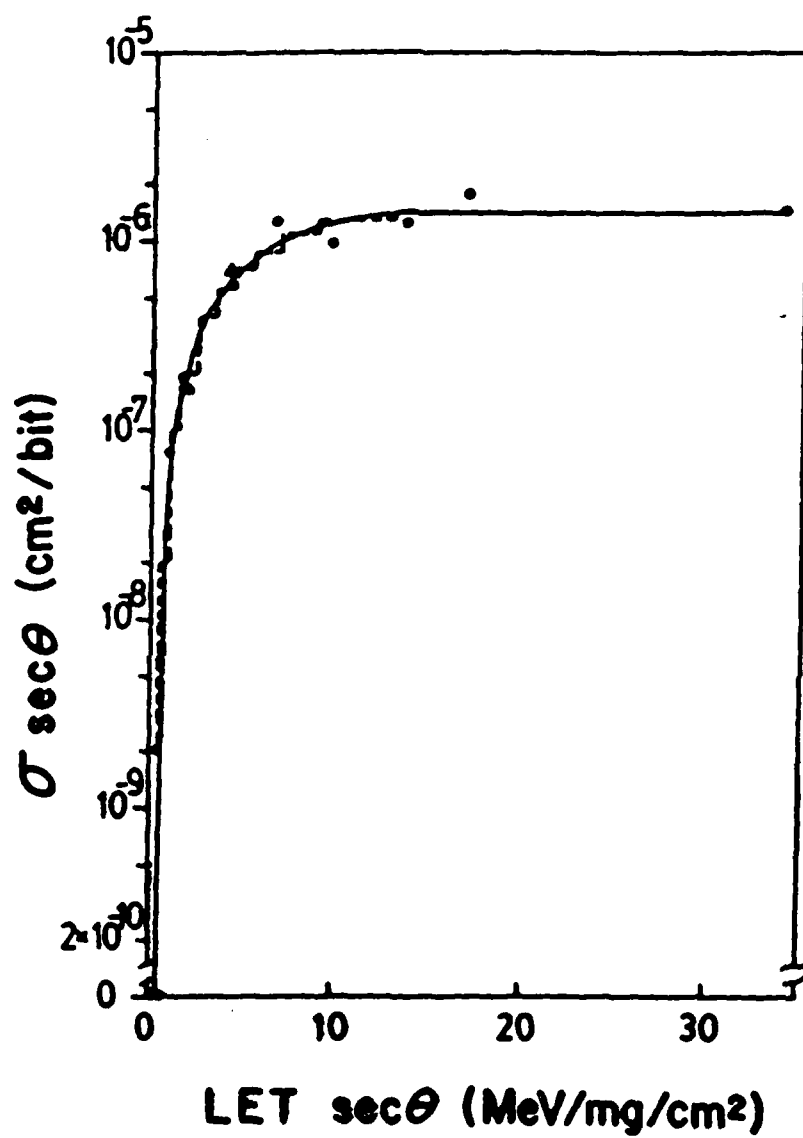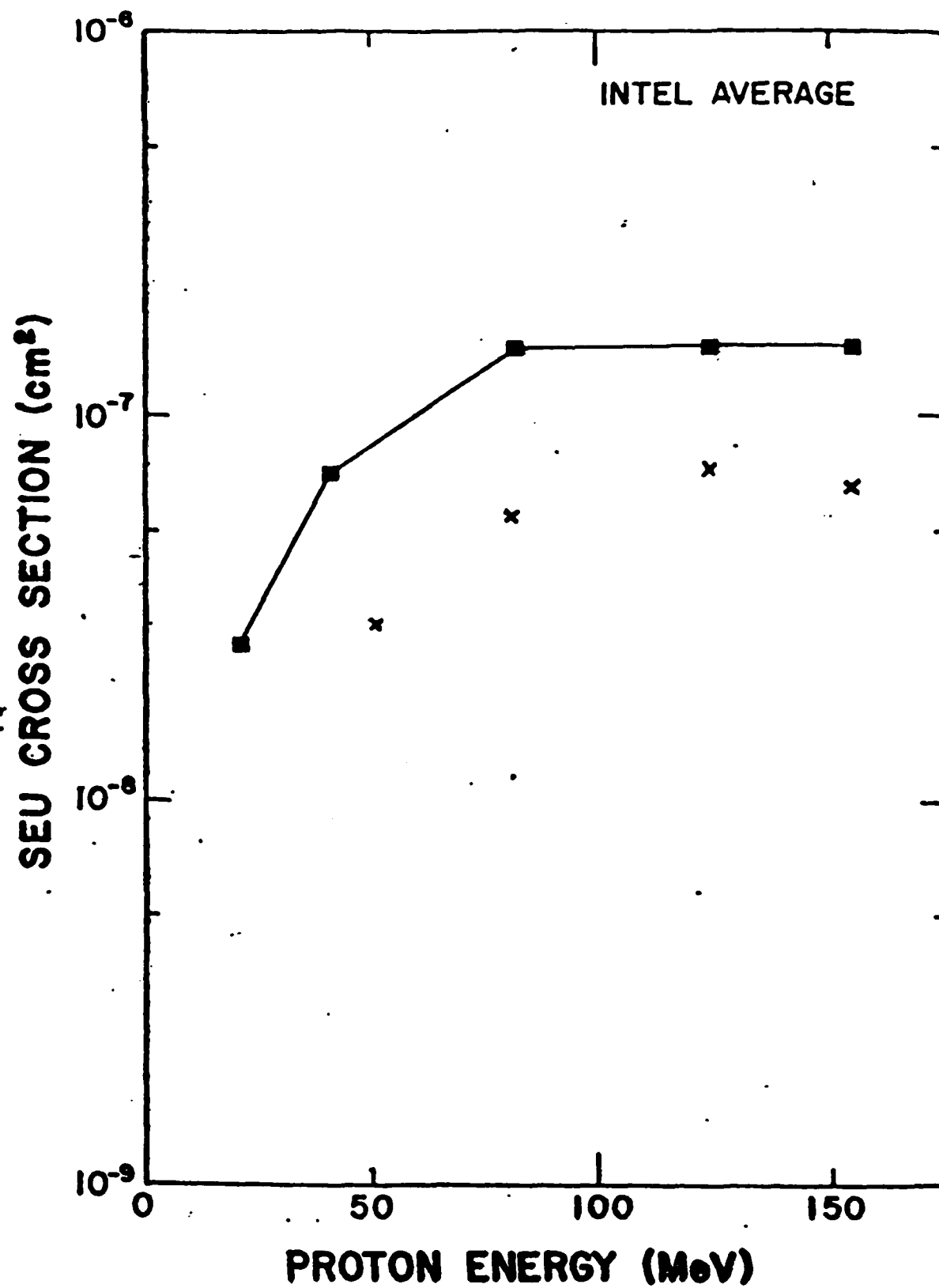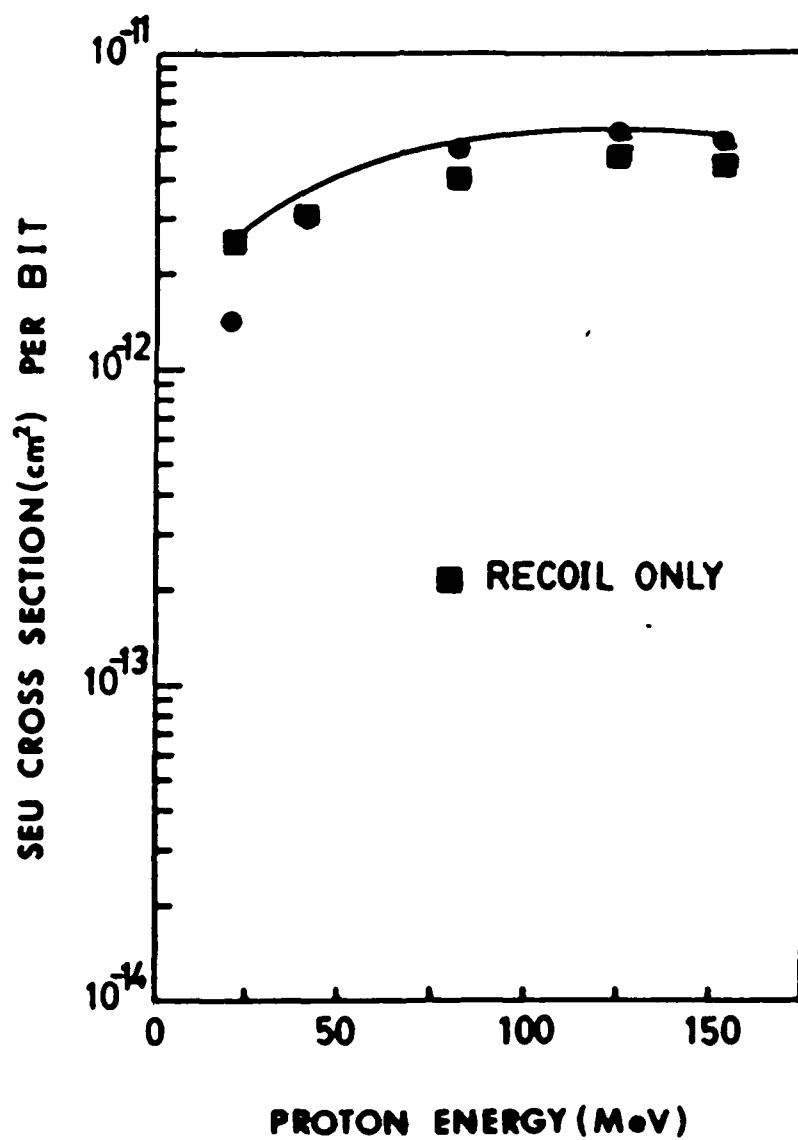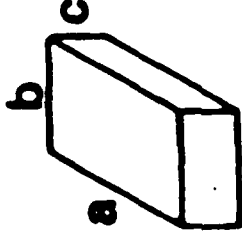
INTEGRAL LET SPECTRUM

COSMIC RAY UPSET RATES

WANT APPROXIMATE DEVICE SENSITIVITY IN TERMS OF UPSET RATE IN REFERENCE ENVIRONMENT

- AS FUNCTION OF GEOMETRY AND CRITICAL CHARGE

$$R \sim \frac{a \times b \times c^2}{Q_c^2}$$

- AS FUNCTION OF DEVICE AREA AND CRITICAL LET

$$R \sim a_L / L_c^2$$

IF DIMENSIONS IN μm AND CHARGE IN pC

$k = 5 \times 10^{-10}$ GIVES R IN UPSETS/BIT-DAY

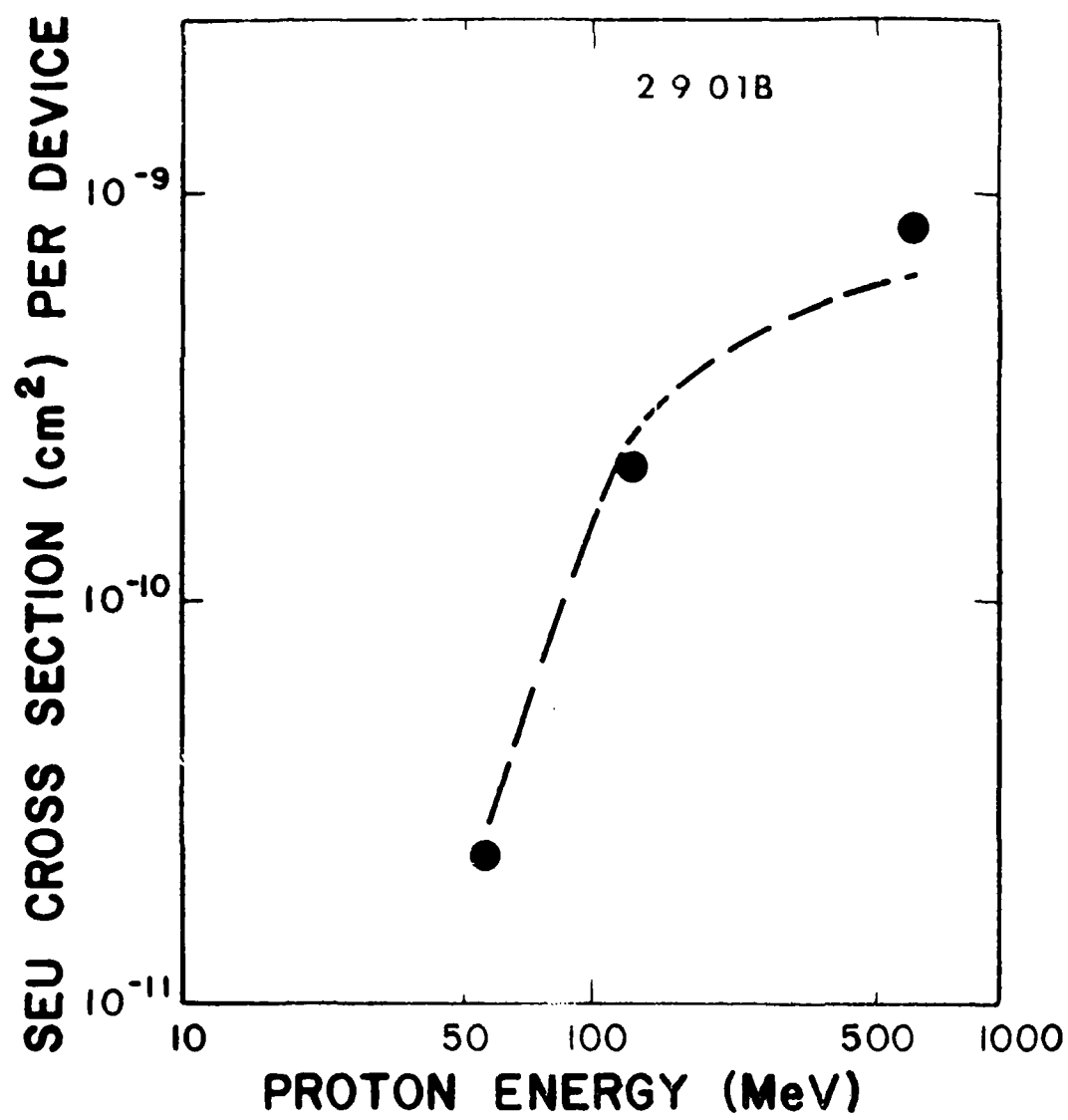FOR 10% WORST CASE GEOSYNCHRONOUS ENVIRONMENT WITHIN A FACTOR OF TWO OF EXACT CALCULATION

ALGORITHM PREDICTIONS FOR 2164A

(ADAM'S 90% WORST CASE ENVIRONMENT)

TECHNIQUE	APPROXIMATION	UPSETS/BIT–DAY
DETAILED CALCULATION	SINGLE (50x)	3.3 E −5
	MULTIPLE	2.7 E −4
FIGURE OF MERIT	SINGLE (50x)	3.7 E −5
(PETERSEN ET AL)	SINGLE (30x)	5.5 E −5
	SINGLE (0.1x)	2.7 E −3
	MULTIPLE	1.65 E −4

Fig (7)
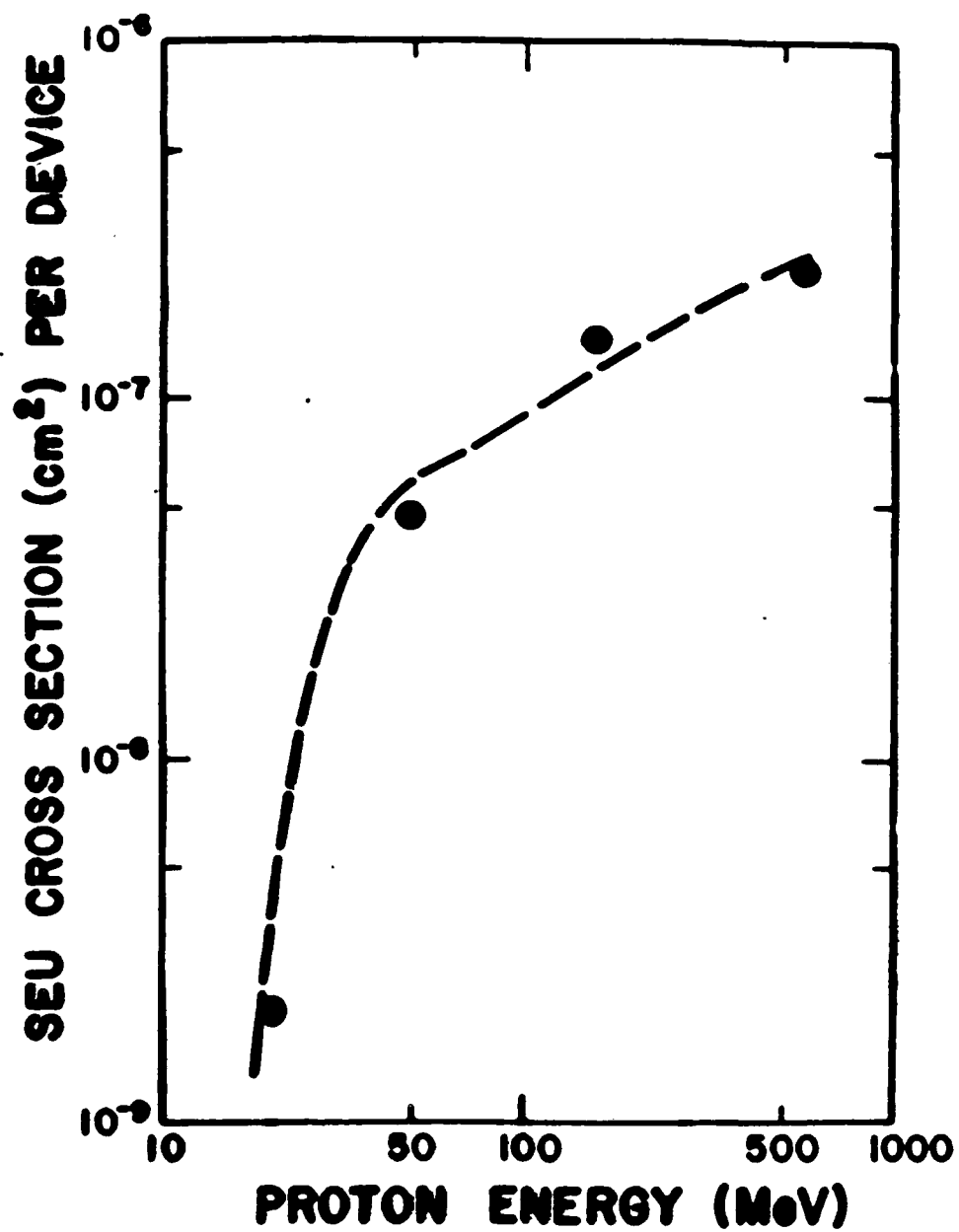
TO REDUCE SINGLE EVENT UPSETS

MICROSTRUCTURE

* INCREASE CRITICAL CHARGE

* DECREASE FEATURE SIZE

* REDUCE FUNNEL AND DIFFUSION CONTRIBUTIONS TO COLLECTED CHARGE

  - INSULATION
  - WELLS
  - EPI LAYER

* CHANGES IN GEOMETRY

CIRCUIT ELEMENT — FLIP FLOP

*RESISTORS

*DIODES

SYSTEM

* ERROR CORRECTION BY SOFTWARE

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OUTPUT

INPUT

V_{DD}

P N P

N P N

DEPLETION REGIONS

SAPHIRE SUBSTRATE

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P-WELL

N EPI

N+SUBSTRATE

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SANDIA TEST STRUCTURE

Single Event Upset Effects and Hardening
CMOS Hardening